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Feasibility Study for a Field Sampling Program to Monitor Impacts resulting from In-situ Heavy Oil Subsurface Disposal Practices

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MANAGEMENT PERSPECTIVE

Starting in 1983 Environment Canada let a series of contracts to Alberta Research Council (ARC) to better:

- i) define the geological and hydrological constraints on subsurface fluid injection;
- ii) characterize wastewaters currently being injected at in-situ oil sands/heavy oil plants in Alberta; and
- iii) investigate phenol partitioning in the laboratory to simulate waste fluid - reservoir rock interactions.

These studies were co-ordinated with the Alberta Department of the Environment's hydrogeological modeling work for the Cold Lake area which was also carried out by ARC.

Recognizing the need to verify theoretical and laboratory studies with field data and recognizing that the collection of field data would be expensive, a study to look at the feasibility and cost associated with a field program to monitor impacts resulting from waste fluid injection in deep sedimentary formations in the oil sands and heavy oil areas of Alberta was initiated in 1986. The results of this study are contained in this report.

PERSPECTIVE DE GESTION

Environment Canada a accordé, depuis 1983, un certain nombre de marchés au Alberta Research Council (ARC) afin:

- i) de définir plus précisément les contraintes géologiques et hydrologiques auxquelles est soumise l'injection souterraine de fluide;
- ii) de caractériser les eaux résiduelles obtenues aux usines de récupération de pétrole lourd/des sables bitumineux par le procédé in situ en Alberta, et qui sont actuellement évacuées par injection;
- iii) d'étudier la séparation du phénol en laboratoire afin de simuler les interactions fluides résiduels-roche réservoir.

Ces études ont été faites en coordination avec le ministère de l'Environnement de l'Alberta, dont les travaux de modélisation hydrogéologique pour la région de Cold Lake avaient également été effectués par le ARC.

Les études théoriques et les travaux de laboratoire devant nécessairement être validés par des données recueillies sur le terrain et compte tenu du coût élevé de la collecte de ces données, une étude a été entreprise, en 1986, pour déterminer la faisabilité et les coûts d'un programme sur le terrain visant à contrôler les impacts découlant de l'injection de fluides résiduels dans des formations sédimentaires profondes dans les régions de l'Alberta où il y a des sables bitumineux et du pétrole lourd. Les résultats de cette étude sont présentés dans ce rapport.

FEASIBILITY STUDY FOR A FIELD SAMPLING PROGRAM
TO MONITOR IMPACTS RESULTING FROM IN-SITU
HEAVY OIL SUBSURFACE DISPOSAL PRACTICES

By: INTERA Technologies Ltd.

For: Conservation and Protection
Environment Canada

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FEASIBILITY STUDY FOR A FIELD SAMPLING PROGRAM
TO MONITOR IMPACTS RESULTING FROM IN-SITU
HEAVY OIL SUBSURFACE DISPOSAL PRACTICES

PREPARED FOR:
CONSERVATION AND PROTECTION
ENVIRONMENT CANADA

BY:
INTERA TECHNOLOGIES LTD.
CALGARY AND OTTAWA

JULY 1987

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ABSTRACT

This report evaluates the feasibility of a field sampling program to monitor impacts resulting from waste fluid injection in deep sedimentary formations in the oil sands and heavy oil areas of Alberta. This evaluation was completed through assessment of the liquid waste disposal situation in the Cold Lake area, Alberta and the design of a field sampling program. The assessment of the liquid waste disposal problem was based on review of existing hydrogeological data and theoretical calculations for each injection horizon using available data. From both of these studies, it is concluded that reliable assessment of the impact of waste fluid injection requires more definitive field data. The field sampling program was designed using:

- a) a hydrostratigraphic unit evaluation in conjunction with constraint mapping for siting wells to assess background conditions and to monitor the impact of waste injection and
- b) a detailed review of field testing methodologies.

Three potential waste fluid injection horizons; the Mannville Group, the Cooking Lake - Beaverhill - Watt Mountain Group and the Cambrian/Granite Wash, were evaluated for the study area using constraint mapping. Depending on the location (i.e., township) of waste disposal, any one of the three zones may be suitable for such operations. However, the preferred horizons do not always agree with those currently in use.

Three different field sampling programs were developed as part of this study. These include a monitoring program in existing wells, a limited testing program in existing wells and a full scale testing program in a newly drilled well. The recommended full scale testing program includes geological investigations, geophysical logging, a hydrogeochemical sampling program, hydraulic testing and a long term monitoring program. The recommended monitoring program includes continuous fluid pressure measurement and periodic water quality sampling from each of the three injection formations and adjacent confining units in a single borehole.

RESUME

Ce rapport a pour objet d'évaluer la faisabilité d'un programme d'échantillonnage sur le terrain visant à contrôler les impacts découlant de l'injection de fluides résiduels dans des formations sédimentaires profondes dans les régions de l'Alberta où il y a des sables bitumineux et du pétrole lourd. Cette évaluation a été réalisée par l'examen de la situation de l'élimination des déchets liquides dans la région de Cold Lake (Alberta) et la mise au point d'un programme d'échantillonnage sur le terrain. Le problème de l'élimination des fluides résiduels a été étudié au moyen des données hydrogéologiques existantes et des calculs théoriques pour chaque niveau d'injection grâce aux données disponibles. Les deux études révèlent que l'évaluation fiable de l'impact de l'injection de fluides résiduels nécessite des données d'expérimentation plus précises. Le programme d'échantillonnage sur le terrain a été conçu et comportait une évaluation de l'unité hydrostatigraphique ainsi que de la cartographie des contraintes pour situer les puits afin d'évaluer les conditions ambiantes et de contrôler l'impact des injections de fluides résiduels, d'une part, et un examen détaillé des méthodes d'essai sur le terrain, d'autre part.

Trois (3) niveaux possibles d'injection de fluide résiduel ont été examinés dans le secteur de l'étude par la technique de la cartographie des contraintes: le Groupe Mannville; le Groupe Cooking Lake, Beaverhill, Watt Mountain; le Cambrian/Granite Wash. En fonction de l'endroit, c'est-à-dire le canton, où se fait l'évacuation des fluides résiduels, l'une quelconque des trois zones peut se prêter à ces opérations; toutefois, les niveaux de prédilection ne concordent pas toujours avec ceux actuellement utilisés.

Trois (3) programmes d'échantillonnage sur le terrain ont été élaborés dans le cadre de cette étude. Il s'agit notamment d'un programme de contrôle dans les puits déjà forés, d'un programme d'essai limité dans les puits en déjà forés et d'un programme complet dans un puit nouvellement foré. Le programme d'essai complet recommandé comporte des enquêtes géologiques, la diagraphe géophysique, un programme d'échantillonnage hydrogéochimique, des essais hydrauliques et un programme de contrôle à long terme. Le programme de contrôle recommandé comporte la mesure systématique de la pression du fluide et un échantillonnage périodique de la qualité de l'eau dans chacune des trois formations où se fait l'injection et dans les unités adjacentes au moyen d'un seul sondage.

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CONCLUSIONS

The main conclusions of this study are:

- Based on existing information from the oil industry, ERCB, ARC, and other sources, there is considerable uncertainty in regional hydrogeological conditions (i.e., formation permeability, formation pressures, and groundwater flow directions) especially the hydraulic parameters of the potential disposal formations for the study area in general and the Cold Lake area in particular. These uncertain subsurface conditions complicate any assessment of potential waste fluid injection impacts in the study area using modeling techniques. Reliable assessment of the impact of waste fluid injection requires more definitive field information.
- An assessment of the impact of waste fluid injection should also consider the potentially deleterious effects of hydrofracturing, abandoned oil and gas wells, poor well construction techniques, lack of strict well decommissioning regulations and casing/completion failures. These potential pathways of waste fluid migration may compromise the integrity of confining units surrounding a disposal horizon.
- Three stratigraphic horizons; Mannville Group, Cooking Lake - Beaverhill Lake - Watt Mountain Group and Cambrian/Granite Wash, were evaluated using constraint mapping to determine their suitability as waste fluid injection zones. Suitability was assessed on a township by township basis throughout the study area. The results of the constraint mapping exercise indicated that some currently operating injection wells are not injecting waste to the most suitable disposal zone.

- The constraint mapping exercise suggests that facilities to assess background hydrogeological conditions should generally be located in areas remote to existing injection operations. However, facilities to monitor the impact of waste injection should be located in areas close to existing injection wells.
- The extent of waste fluid injection in terms of migration of waste front and radius of pressure build-up are theoretically dependent on hydrogeologic properties of the injection formation (thickness, porosity, hydraulic conductivity, and specific storage) and waste injection practices (injection flowrate and duration). Given uncertainty in available hydraulic properties field measurements are required for reliable assessment of such an impact.

Additional conclusions relating to a field testing and monitoring program are:

- Field program options have been developed to determine the physical properties of the injection zone and the confining formations in order to assess the potential environmental impact of disposal operations. The field programs include geologic, geophysical, hydrogeologic, geochemical and monitoring studies.
- Three different field testing and monitoring programs were developed as part of this study. These include: 1) a monitoring program in existing wells; 2) a limited testing program in existing wells; and 3) a full scale testing program requiring drilling of a new well. The approximate total costs for these field programs are: 1) \$231,400; 2) \$329,400; and 3) \$1,204,200. The total field program costs have also been broken down and expressed as annual costs for one, two and three year program options.

- A drill water tracer program is required for use during drilling of a new borehole in order to ensure reliable and representative groundwater samples.
- A suite of geophysical logs is required for both cased and uncased boreholes.
- Formation fluids should be sampled both during drilling and subsequent to completion of monitoring facilities.
- Swabbing of the drill string or monitoring well, in conjunction with the use of pressurized sample vessels, is selected as the most appropriate fluid sampling technique.
- Hydraulic testing should consist of single packer tests performed coincidently with drilling operations and double packer tests to be performed following drilling and logging operations.
- Utilization of existing cased wells will lead to a number of uncertainties which are likely to compromise the integrity of the monitoring and testing program.
- Monitoring facilities are required which allow pressure monitoring and fluid sampling in a minimum of six hydrostratigraphic units.
- A multiple piezometer nest is the preferred well completion. This completion consists of six narrow-diameter piezometers each completed in a different hydrostratigraphic unit and isolated from adjacent intervals.

RECOMMENDATIONS

- With regards to priority for field monitoring system installation, it is recommended that highest priority be given to monitoring installations which will assess the impact of waste fluid injection at sites of immediate concern. Of second priority is the installation of a monitoring system to assess background hydrogeological conditions.
- The full scale testing program should be implemented using a recently drilled borehole. The borehole should be completed using a multiple piezometer nest completed in each of the three injection horizons and adjacent confining units.
- The full suite of parameters present in the waste fluids injected at different sites should be reviewed to identify potential indicator parameters which are common to all waste streams. These parameters would be added to the existing list of indicator parameters.
- More detailed investigations should be conducted to further investigate candidate areas for the installation of a monitoring system. This would include, but not be limited to, resolving of land access, obtaining permission to drill, performing a detailed study of local geology and identifying potential complicating factors.

- The effects of hydrofracturing as potential avenues of waste fluid release should be studied in greater detail. Regulations should be developed regarding hydrofracturing in waste fluid injection wells so as to limit the potential for vertical fluid migration.
- Based on the results of laboratory and field based studies, predictive simulations should be performed to assess the likely impact of waste fluid injection. Simulations should account for fluid flow and solute transport as well as the effects of heat flow in steamed zones. Solute transport simulations should account for waste fluid/host formation interactions and chemical species of varying mobility and aquatic toxicity.

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- CPA In-Situ Heavy Oil Environmental Subcommittee
- Saskatchewan Environment, Land Protection Branch
- Saskatchewan Water Corporation
- Environment Canada, Saskatchewan District Office
- Environment Canada, National Hydrology Research Institute
- Environment Canada, Industrial Programs Branch

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1.0 INTRODUCTION

1.1 BACKGROUND

Extensive heavy oil deposits are present in the Lower Cretaceous formations in a large area centered on Cold Lake, Alberta. Heavy oil extraction and processing has been conducted, at various levels of effort, for more than two decades. Public concern has been expressed over the potential environmental implications of both the heavy oil extraction and waste water disposal operations in this area. This concern is directed at the possibility for contaminants to reach and pollute potable groundwater supplies.

The potential for pollution of potable groundwater as well as surface water supplies by process effluents is largely unknown. Over the past few years, several studies have been directed at assimilating information from the oil industry and other sources (ARC, 1985a-k; Meneley, 1983a-b). These studies have provided considerable insight to the potential problems and have raised a number of questions regarding the suitability of subsurface strata for accepting waste fluids. At this point in time, it is prudent to consider verifying existing data and to address the questions raised in previous studies. To this end, the feasibility of a field testing and monitoring program is considered to further investigate the potential for release of pollutants.

1.2 OBJECTIVES

The overall objective of this study is to verify through a field based testing program the findings of theoretical and laboratory studies performed to date. The study, as outlined in the Terms of Reference, is to include the design of a detailed field program to:

- Provide the geologic, hydrogeologic and hydrochemical data to aid the calibration and verification of theoretical and laboratory information; and

- Address the issue of impact of subsurface waste disposal in the Cold Lake area.

The study objectives are further refined to include consideration of different levels of effort in the field program. More specifically, the use of existing boreholes or wells is included along with the use of newly drilled boreholes.

The study area, as defined in the Terms of Reference, is to include portions of both Alberta and Saskatchewan (Figure 1.1). The specific area includes Townships 55 to 69, Ranges 16 to 27, west of the 3rd meridian in Saskatchewan and Townships 55 to 69, Ranges 1 to 17, west of the 4th meridian in Alberta.

1.3 METHODOLOGY

This study includes an extensive review of existing reports pertinent to the study area as well as the regulatory restrictions governing waste fluid injection and borehole installation. This review is followed by a discussion of the factors perceived to control the migration of waste fluids in the study area and a preliminary assessment of the potential extent of the impact from disposal operations.

The factors governing the suitability of a candidate waste injection horizon are then assessed as they pertain to different portions of the study area to arrive at recommended injection zones. The study area is further evaluated to determine the most suitable locations for monitoring wells to assess both background conditions and the impact of waste fluid injection.

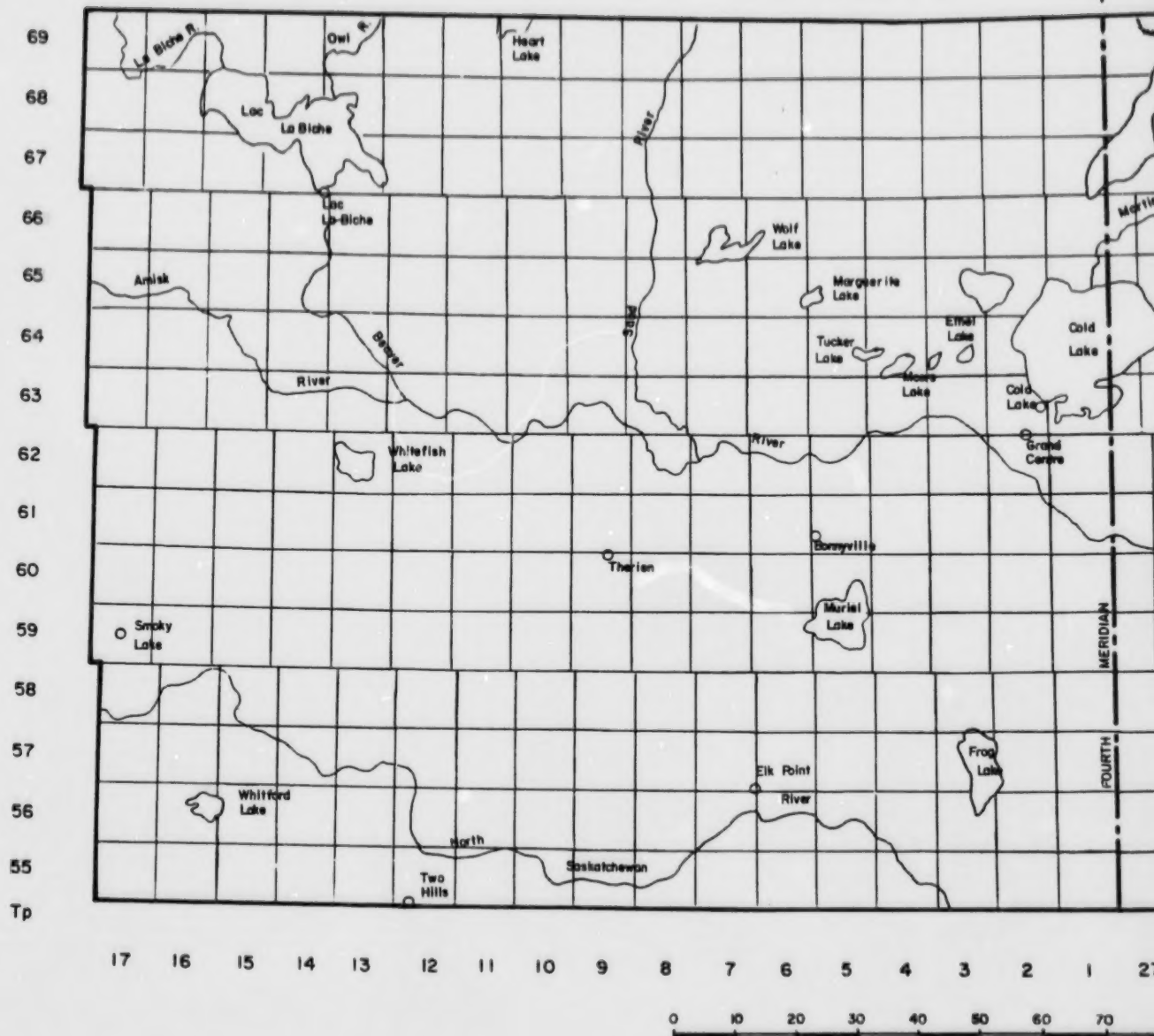
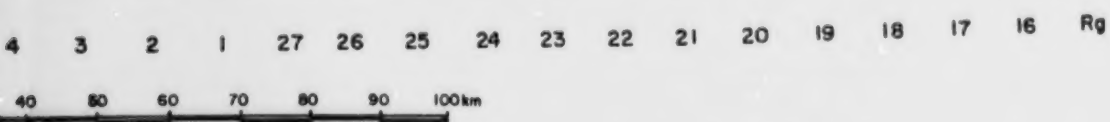
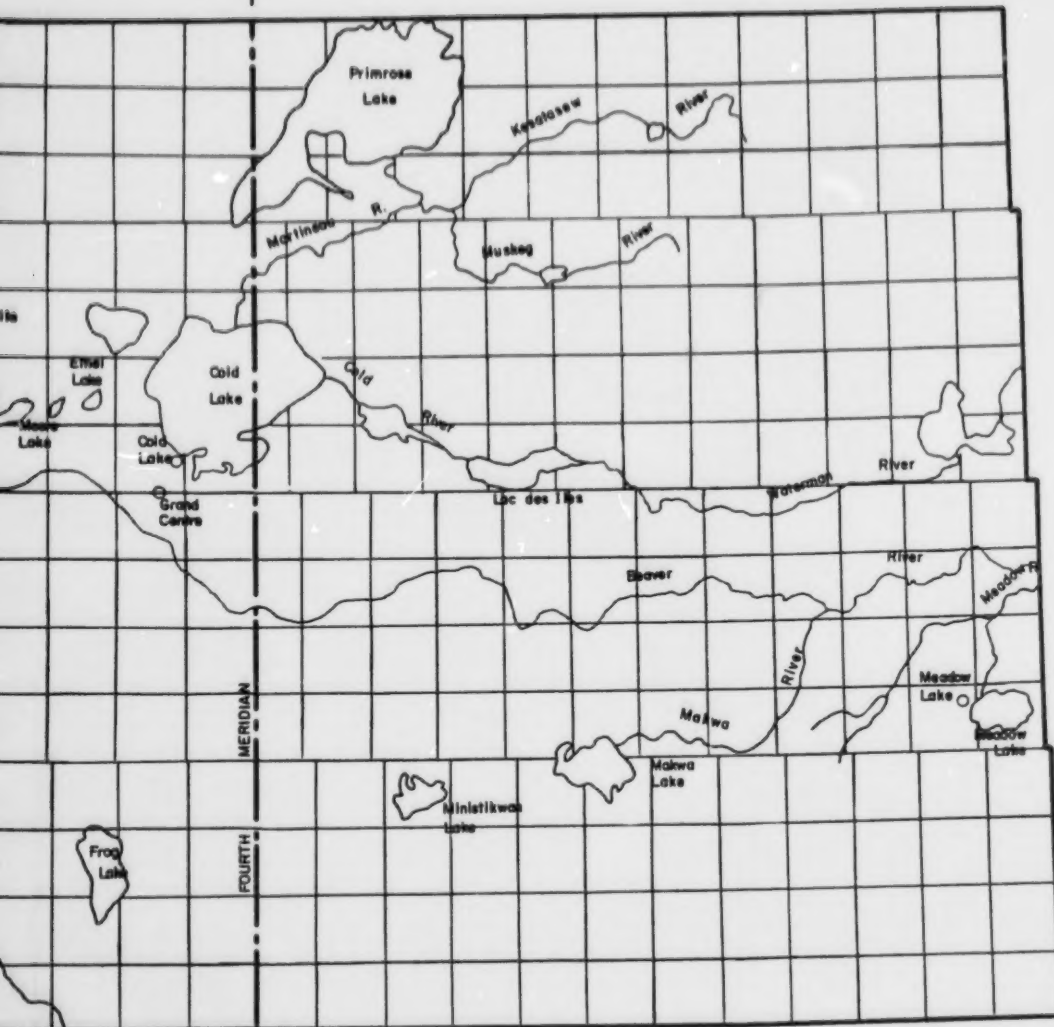


FIGURE 1-1 STUDY AREA

SASKATCHEWAN



UDY AREA

The field testing methodology is discussed in detail for geologic, geophysical, geochemical and hydraulic testing programs. The theoretical basis and the rationale for the different tests are discussed leading up to recommended methodologies for this testing program. The levels of effort investigated for the field program include a full scale testing, limited scale testing and strictly a monitoring program.

Alternatives for long term monitoring in terms of well completions are evaluated and the optimal completion recommended.

Project management strategies are evaluated which are specific to implementation of the testing and monitoring program recommended.

Cost estimates are prepared for each of the three levels of effort considered. These costs are derived based on implementation of the field testing and monitoring programs recommended in this study.

2.0 ASSESSMENT OF LIQUID WASTE DISPOSAL SITUATION

2.1 REVIEW OF EXISTING DATA

2.1.1 Alberta Research Council/Alberta Environment Studies

In 1982, Alberta Research Council (ARC) and Alberta Environment (AE) launched a jointly funded program (50% each) to study the regional hydrogeology of the Cold Lake area of Alberta. The objective of the study was to "determine the baseline hydrogeological situation prior to development of commercial in-situ recovery operations in the oil sands deposit because of the possible impact these might have on the natural flow system, specifically on the nearsurface potable groundwater resources" (ARC, 1985f). Initially, the study area consisted of Tp 55-69, Rg 1-14, W4th meridian in Alberta but has since been extended into Saskatchewan (Tp 55-69, Rg 16-27 W3rd meridian) (see Figure 1.1). ARC has been responsible for conducting essentially all of the work on the study which has lead to the submission of a series of six reports with an atlas of 240 maps and a hardcopy of the data base in early 1985. This submission to AE included individual volumes on the database developed, regional geology, hydrogeochemistry, hydrodynamics, hydrometeorology and numerical simulation of groundwater flow. Although this study provided an extensive coverage of the above topics it was limited to the geologic strata above the Prairie (Evaporite) Formation (Figure 2.1) and to the Alberta portion of the study area. The study is subsequently being extended to cover these limitations and is ongoing at this time (i.e., Study reports are not yet available). Extension of the study area to the south to cover the Lindbergh heavy oil area is also under consideration. As a result, only the portion of the ARC/AE study completed as of early 1985 has been utilized in this study.

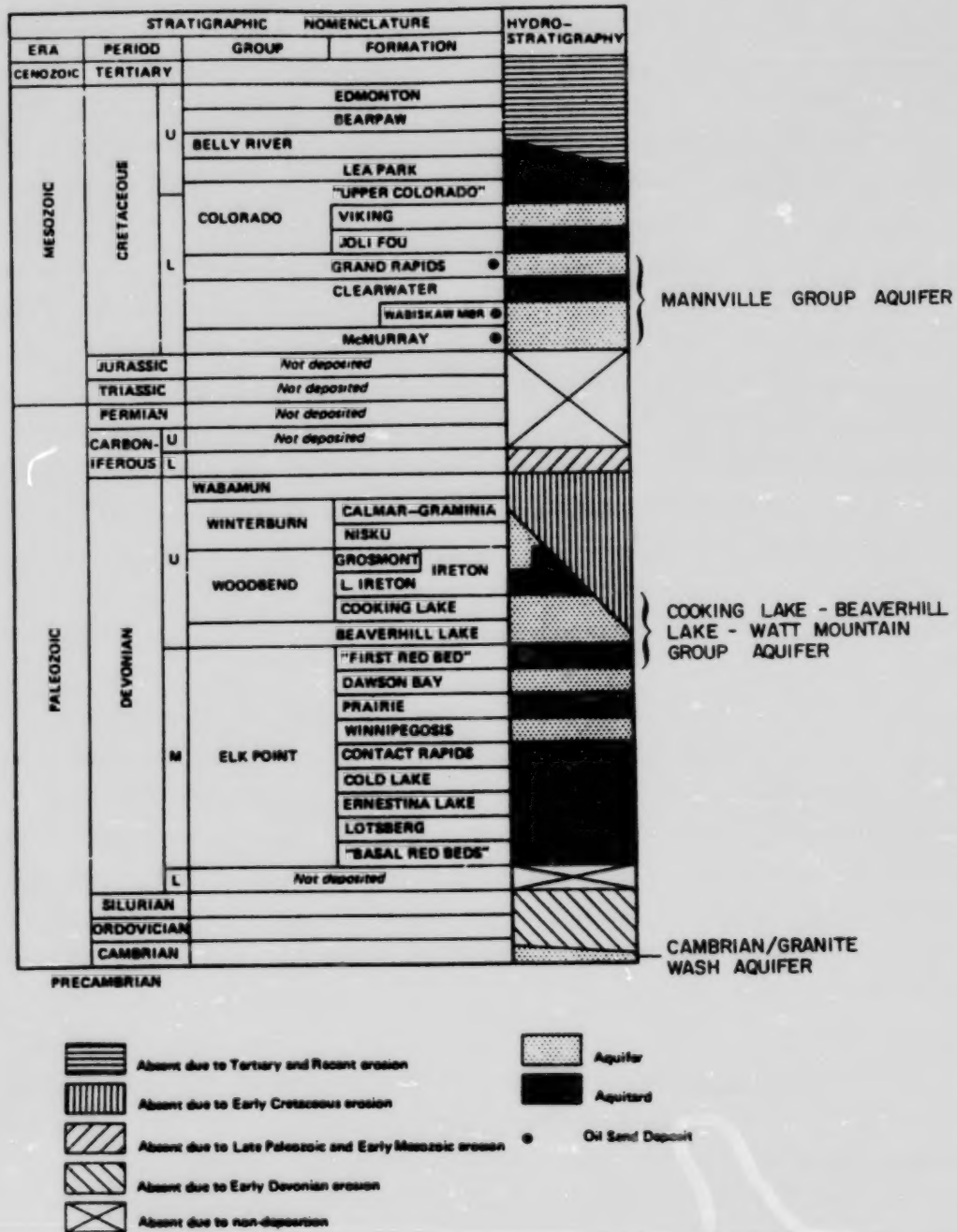


Figure 2.1 Generalized Stratigraphy and Hydrostratigraphy of the Study Area (after ARC, 1985a; 1985g)

2.1.1.1 Data Base. ARC (1985f), in order to assimilate the large amount of data available related to the hydrogeology of the Cold Lake area, developed comprehensive data base management software to input, sort, interpret and synthesize hydrogeologic data. The data base includes information on location, stratigraphy, drill stem tests, cores and formation water chemistry for which the data base software provides capabilities to allow "cross-linking" (i.e., correlating). The stratigraphy and core data are based on information in the Energy Resources Conservation Board (ERCB) files for which data were available on 3100 wells in the study area. The data base software has the further capabilities of utilizing the properties of any point in 3-D to produce a map or as input in determining statistical or mathematical parameters/relationships. The data base is interfaced with plotting software which produces maps and cross-sections at a scale of 1:50,000. Hardcopies can be produced for the information within the data base. Furthermore, the data base structure is compatible with the needs of groundwater flow simulation models also used as part of this study.

An extensive quality control program was implemented to ensure the representativeness of the data contained within the data base. Well logs were reinterpreted to identify the position of major geologic controls. The controls were identified by a large number of data points from which consistent interpretations of geology could be performed. Hydraulic and chemical data are plotted in a number of formats to identify anomalies: Incorrect data are corrected and erroneous data deleted.

2.1.1.2 Regional Geology. The ARC (1985g) review of regional geology summarizes all geological units in the Cold Lake study area from the oldest Precambrian to the more recent Quaternary. The geologic history of the area situated within the Western Canadian Sedimentary Basin is discussed and the impacts on the current stratigraphy (Figure 2.1) are identified. Surface contour, geologic and isopach maps at a scale of

1:1,000,000 have been produced for a number of geologic units. These maps were produced from ERCB data which have been assimilated into the ARC database. Some discussion of the hydrogeology is provided but this is limited to the strata above the Middle Devonian Prairie Formation and below the Quaternary.

The discussion of geology provides significant insight into the potential impacts of subsurface waste disposal in the study area. For instance, early Devonian erosion of the Silurian and Ordovician shale and carbonate formations resulted in erosion of the Cambrian (Deadwood) Formation to the north of the Meadow Lake Escarpment resulting in a thinning in this direction. The significance of dissolution of the Prairie Formation and the impact of the pre-Cretaceous Unconformity (Figure 2.2) are also discussed. The Prairie Formation is an evaporite of Middle Devonian age which is considered an aquitard where intact. The formation has undergone dissolution at its northeastern limit likely resulting in direct hydraulic communication between the Keg River/Methy/Winnipegosis carbonate reefal structure and the Cooking Lake - Beaverhill Lake - Watt Mountain aquifers. Furthermore, evidence of collapse features have been observed in the vicinity of the solution edge of the Prairie Formation. These collapse features have been noted in structure contours of various marker horizons extending into the Upper Cretaceous (ARC, 1985g).

The pre-Cretaceous Unconformity (PCU) is an erosional zone situated between the Devonian and Cretaceous age formations. The presence of the more permeable PCU results in direct hydraulic communication between the Upper Devonian Cooking Lake - Beaverhill Lake Group - Watt Mountain Formation (where it subcrops) and both older and younger Devonian formations through flow along the PCU. Furthermore, where both the Ireton and the Prairie Formation are absent (Figure 2.2), hydraulic communication may exist throughout the entire geologic

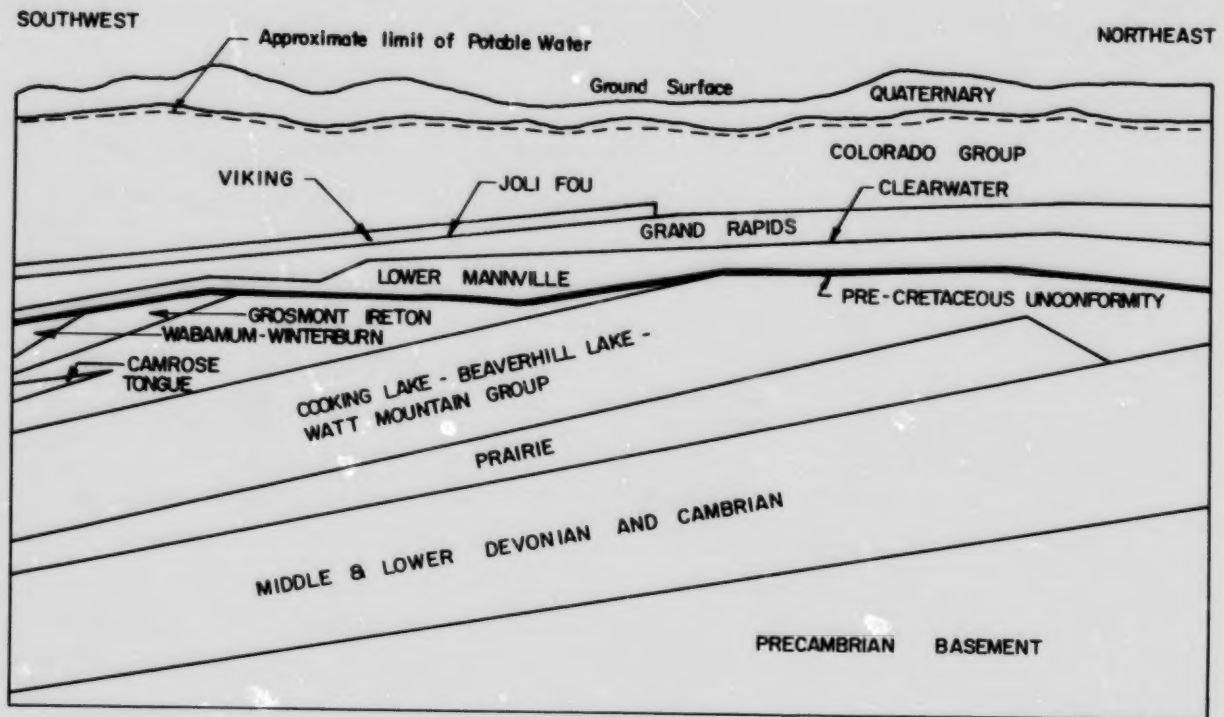


FIGURE 2-2 CROSS - SECTION OF THE GEOLOGY OF THE ALBERTA PORTION OF THE STUDY AREA (After ARC, 1985g)

sequence from formations of Cretaceous age to formations of Lower Devonian age. As a result, there are several area within the study areas where formations of significantly different age are hydraulically connected. This has significant impacts on a deep well injection program.

2.1.1.3 Hydrochemistry. The study of hydrochemistry was conducted in part by ARC who limited their efforts to the post-Prairie Phanerozoic formations and in part by AE who dealt solely with the Quaternary. The hydrochemistry data reportedly aided considerably in interpretation of the potentiometric surfaces through correlation of groundwater flow directions with hydrochemical trends.

The ARC portion of the study again relied on data available in the ERCB data files which were edited using sorting and culling software developed in conjunction with the ARC data base software. As a result of data editing, only 23% of the 2400 available chemical analyses were deemed of sufficient reliability to include in the data base. Criteria for initial elimination of a particular chemical analysis includes (ARC, 1985h):

- obvious contamination from cementing, acid washes and KCl muds;
- calcium and magnesium reported as equivalent calcium;
- either one of Ca, Mg, Cl, SO₄, HCO₃ or CO₃ is missing;
- unacceptable cation/anion balance (only where sodium and potassium determined independently (i.e., not by calculated difference));
- recalculation of sodium and total dissolved solids (TDS) (usually incorrect);
- TDS (evaporated at 110°C);
- TDS (ignition);
- calculation of density and resistivity.

Subsequently, additional outliers are identified using cumulative frequency plots of chloride (selected due to its conservative nature) in which the data points which occur in the less than 10% and greater than 90% brackets are removed. Although these culling techniques do not account for a number of usual quality control considerations, such as poor collection procedures and inadequate sample preservation (for which insufficient information is usually available), they have been reported to perform well in identifying general regional trends.

The ARC study consisted of reviewing water chemistry data for a number of aquifers as follows:

- Cooking Lake - Beaverhill Lake - Watt Mountain aquifer;
- Leduc Formation aquifer;
- Camrose Tongue aquifer;
- Grosmont Formation aquifer;
- Wabamun - Winterburn aquifer;
- "Lower-Mannville" aquifer;
- "Upper-Mannville" aquifer;
- "Viking Sandstone" aquifer; and
- Intra-Colorado aquifer.

As a result of these studies, five distinct hydrochemical trends were identified (ARC, 1985f; 1985g; 1985h):

1. The salinity decreases to the northeast in the Cooking Lake - Beaverhill Lake - Watt Mountain aquifer consistent with regional trends in the potentiometric surface and hydraulic gradient.
2. The salinity decreases to the north in the Camrose Tongue, Grosmont Formation and Wabamun - Winterburn aquifers. These aquifers are isolated from the regional flow system by the Ireton Formation aquitard and are in

stratigraphic and lithologic connection with the Alberta Shelf to the south. The Grosmont is possibly connected to the overlying Lower Mannville Group along the eastern limit of the Grosmont.

3. The Lower Mannville Group aquifer hydrochemistry shows three distinct trends: (i) in the south, salinity gradients are directed to the north; (ii) in the northeast, salinity gradients decrease and change direction to the northeast; (iii) in the northwest, lower salinities in the area of the Grosmont Formation subcrop have been interpreted to suggest downward flow of formation fluid into the Grosmont. A similar situation occurs in the subcrop area of the Cooking Lake - Beaverhill Lake - Watt Mountain Formation where salinity trends in the overlying Lower Mannville Group change from north to northeast.
4. Salinity trends in the Upper Mannville Group aquifer are a subdued replica of those in the Lower Mannville Group aquifer.
5. The Viking Sandstone hydrochemistry is similar to that of the Upper Mannville Group aquifer but with lower salinities and shallower gradients.

In summary, these results suggest (ARC, 1985h) that the Cooking Lake - Beaverhill Lake - Watt Mountain aquifer is situated within the regional flow system with flow to the northeast and that it is isolated, from overlying aquifers for the most part, by the Ireton Formation aquitard.

Trends in groundwater quality data collected for the Quaternary deposits by AE were summarized as follows:

1. Groundwater quality is characteristic of the proximity of the sampling point to bedrock;
2. Recharge and discharge areas (on the local to intermediate scale) correlate closely and are a major factor in groundwater quality.

2.1.1.4 Hydrodynamics. The hydrodynamics study (ARC, 1985i) consists of two main parts; that which is involved with the interpretive techniques used in processing data and that which comprises an analysis of groundwater flow trends based on a synthesis of point data.

In terms of the interpretive techniques utilized, the hydraulic properties of the Phanerozoic sequence were derived from both core analyses and drill stem tests (DST's) while hydraulic parameters for the Quaternary were primarily from pump tests. It should be noted that the Cretaceous and older formations are of primary concern in the current study of waste disposal and that the younger deposits are not generally considered or reviewed except where they may be affected by waste fluid injection.

The DST and core data presented by ARC required extensive data culling to minimize its uncertainty. In particular, interpretation of DST's was typically complicated as insufficient information was reported to analyze the data. The necessary information was subsequently estimated to facilitate test analysis. In regard to core analysis, it was observed that the parameters reported in core analysis did not compare well with those from DST's. This was attributed to poor documentation of core test conditions (i.e., test fluid, stress) but none-the-less leads to some uncertainty in the meaning of the core data.

In terms of further data manipulation, the permeabilities for adjacent formations were lumped together in several instances where log normal frequency plots were observed to be similar in median and range.

The interpretation of hydraulic parameters is presented as an assimilation of available data in the form of hydraulic head versus depth as well as contour plots of hydraulic heads. Hydraulic head trends in different formations are compared and scenarios are developed as to how anomalies may have arisen. The most noteworthy points are as follows:

1. East of the subcrop limit of the Ireton Formation (i.e., the Ireton Formation pinches out), the Cooking Lake-Beaverhill Lake - Watt Mountain aquifer (or Upper Devonian) is no longer isolated from the Lower Mannville Group and the two are considered, hydrogeologically, as one (see Figure 2.2).
2. Flow directions in the Cooking Lake - Beaverhill Lake - Watt Mountain aquifer are to the northeast following the regional flow pattern.
3. East of the subcrop limit of the Prairie Formation (or "Salt") the Keg River Formation is likely in hydraulic communication with the overlying Cooking Lake - Beaverhill Lake - Watt Mountain aquifer and the Lower Mannville Group (see Figure 2.2).
4. Within the Winterburn - Grosmont - Camrose aquifer (present only west of range 12) the Winterburn and Grosmont aquifers are considered interconnected through the Lower Mannville in their subcrop zone. The degree of interconnection of these aquifers with the Camrose Tongue

is speculative due to a paucity of data but this interconnection is considered likely. In the subcrop zone of the Winterburn and Grosmont aquifers, they are combined with the Lower Mannville across the PCU and considered to act as one aquifer. Groundwater flow directions are primarily to the northwest in this portion of the study area. Flow of groundwater within these aquifers is considered to be within the intermediate groundwater flow system.

5. In the Lower Mannville Group aquifer flow is primarily to the northeast in agreement with regional flow for the eastern portion of the ARC study area. Flow directions in the western half of the study area are more complicated but tend to be to the northwest in the northern portion and southwest in the southern portion.
6. The Clearwater Formation, which is thought to act as an aquitard isolating groundwater flow between the Upper and Lower Mannville, is absent in the southeast portion of the ARC study area allowing flow between these two formations.
7. Pressure head versus depth data for the confining units suggests that groundwater flow is likely upwards across the Ireton Formation aquitard and downwards across the Clearwater, Joli Fou and Colorado Formations aquitards.
8. Flow of groundwater in the Upper Mannville Group is primarily downward with little lateral groundwater movement.

9. The Viking Sandstone is likely within the local groundwater flow regime.

2.1.1.5 Hydrometeorology. This report was prepared primarily to determine the nature of the upper boundary conditions for the numerical groundwater flow simulations. It includes only a portion of the study area, that being the Beaver Creek drainage basin. This report involves collection of surface hydrology data (i.e., lake evaporation, evapotranspiration) and analysis of stream flow and precipitation data to arrive at recharge and run-off estimates.

2.1.1.6 Numerical Simulation. A numerical model of groundwater flow was developed for a portion of the ARC study area. The model was calibrated to natural (unperturbed) conditions with future plans to simulate the effect of waste fluid injection. The modeled area includes the majority of heavy oil pilot plants and is bounded in the east by the edge of the Prairie Formation, in the west by the complex geology of the Camrose Tongue - Grosmont - Winterburn and Leduc carbonate complex. The Primrose Air Weapons Range provides a northern boundary due to lack of subsurface information and the topographic highs north of the North Saskatchewan River, which are surface water divides and likely a local groundwater flow divide, are used as a southern boundary to the modeled area. It should be noted that in most instances the boundaries to the modeled area were apparently derived based on reported hydraulic head values. In terms of the upper boundary conditions for the model, a number of approaches were tried with the one adopted which best reproduced the observed flow configuration. The upper boundary condition which was selected was to fix the hydraulic heads at the top of the Phanerozoic sequence equal to observed heads in the overlying Quaternary aquifers and, where absent, the water table. Furthermore, the Quaternary and Phanerozoic flow systems were considered uncoupled with no recharge to the Phanerozoic from the Quaternary. Subsequent calibration of the model to observed heads lead to an average error of 1.3% with maximum differences of 30 metres observed between predicted and observed heads.

Further modeling is proposed to simulate the effects of waste fluid injection; however, it may be necessary to extend the modeled area to reflect the radius of influence of the pressure build-up. In particular, a number of pilot and commercial operations are presently injecting waste fluids into the Cambrian Age Granite Wash which is not included in the present model. Also, the pressure build-up resulting from injection at higher flow rates and pressures results in a radius of influence beyond the modeled area. It should also be noted, as pointed out in the ARC (1985k) study, that the model developed may only be used for simulation of fluid flow and consequently does not account for heat or solute transport effects.

2.1.2 Alberta Research Council/Environment Canada Studies

A series of studies were conducted by ARC which were fully funded by Environment Canada (EC) with the objective being to identify and assess the nature of waste fluid/host formation interactions in and around the heavy oil producing areas of Alberta. The studies proceeded in three phases which covered a regional geological and hydrogeological reconnaissance and interpretation, a determination of waste water composition from pilot plant operations and a laboratory assessment of fluid/rock interactions. Four oil sands/heavy oil areas were identified and studied for which the one pertaining to the study underway, referred to as the Athabasca Study area, is the only one reviewed in detail in this report. The Athabasca study area covers a somewhat broader area than the current study such that selective information was extracted as pertains to the current study. Individual reports dealing with these subjects are discussed in the following subsections.

2.1.2.1 Regional Reconnaissance. As part of the regional reconnaissance, ARC (1985a) discusses the history of the Western Canada Sedimentary Basin in terms of its impact on the hydrostratigraphy within the study area. The argument that no waste disposal should

occur below the pre-Cretaceous Unconformity (PCU) is developed based on the existence of a hydraulic connection across the PCU between formations of Cretaceous and pre-Cretaceous age which subcrop in the area. As a result, the entire Cretaceous and those formations hydraulically connected are considered to be within the local groundwater flow system such that formation fluids have a lower retention time in the subsurface and may readily flow to the land surface.

ARC (1985a) further discusses the modification in the regional groundwater flow conceptualization which occurs as a result of the presence of the higher relative permeability Upper Devonian and Carboniferous (not present in study area) formations which presumably act as drains affecting much of the sedimentary sequence. It is concluded that these formations, as well as the PCU, should be avoided in siting waste injection facilities.

More detailed studies of the geology and hydrogeology, similar to that conducted as part of the ARC/AE studies discussed in 2.1.1, lead to the development of numerous maps which show hydrocarbon and mineral resources, geology, structure, isopachs, water quality, etc. As a result, many of the diagrams and ensuing discussion are somewhat repetitive. The hydrogeology of only the CBWA is discussed in detail. Of particular interest is the relationship between aquifers and aquitards as illustrated in Figure 2.3. Although this figure extends over an area much larger than the current study area, it is useful to show where various confining units are absent leading to interconnection between aquifers. The absence of confining layers has serious implications to waste fluid migration.

Limited point information including hydraulic properties (i.e., hydraulic conductivity, storativity) and water quality data (i.e., chloride, TDS, etc.) are presented in figure form in the ARC (1985a) study. The most evident trend observed is the drop in

	1	2	3	4
Overlying Aquitard	Ireton	Grosmont		
Injection Aquifer	Cooking Lake	L. Ireton	Cretaceous	
	Beaverhill Lake			
	Watt Mountain			
Underlying Aquitard	Prairie			
	Keg River			

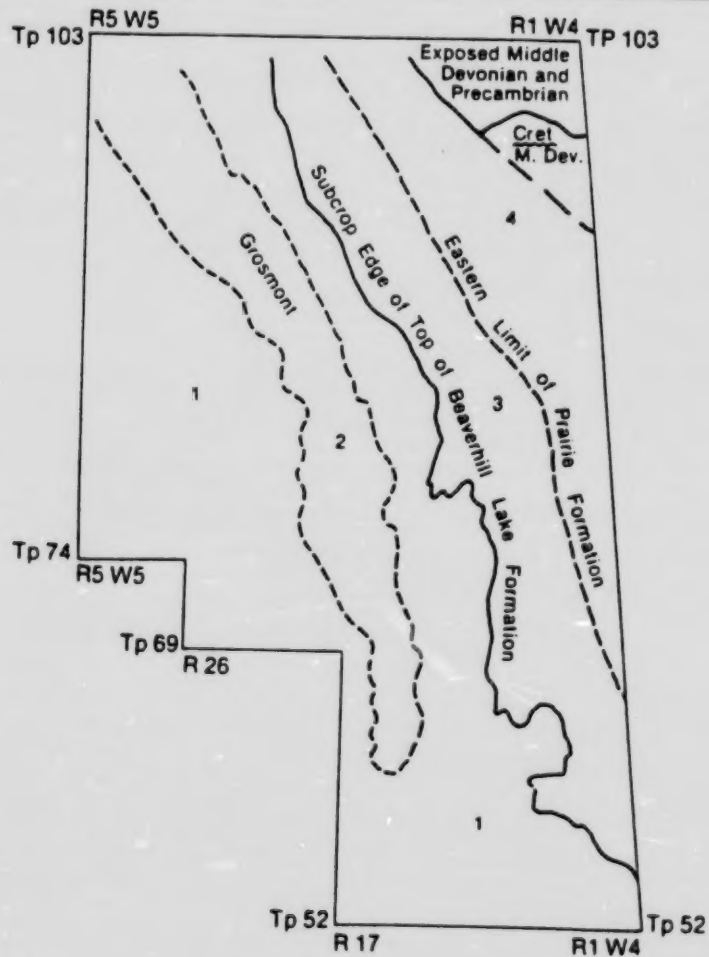


Figure 2.3 Diagrammatic Representation of the Relationship Between the Cooking Lake - Beaverhill Lake - Watt Mountain Aquifer and Adjacent Hydrostratigraphic Units (from ARC, 1985a)

chloride and TDS levels towards the north and east within the current study area. Also, bearing in mind that only six values of hydraulic conductivity are presented, it is not possible to conclusively identify any trends in hydraulic conductivity although the values reported in the southeast (10^{-9} m/s) are approximately two orders of magnitude less than reported elsewhere (10^{-7} m/s).

In terms of resource potential, it is reported that no conventional hydrocarbon resources are known to exist within the CBWA. Essentially all conventional hydrocarbons within the study area are found within the Cretaceous strata with the exception of the crude oil in the Keg River Formation at Senex. Gas fields do exist below the PCU, primarily in the Grosmont Formation, Wabamun Group, Winterburn Group and the reef complex within the Leduc Formation.

Some potential exists for commercial scale extraction of brines from the Keg River and lower Elk Point Group in the southwest portion of the study area with little potential identified for the CBWA and the Cambrian age formations.

In Part 2 of the Phase 1 and 2 report of the ARC/EC study, the results of analyses of selected waste waters and an evaluation of phenol partitioning are presented. In regards to the waste water sample collections, it should be noted that these samples were collected from heavy oil processing units around the province and that they were found to be representative of analyses reported in the literature. In reviewing the water quality analyses of selected waste waters, it was reported (ARC, 1985b) that the waters were primarily of the sodium-chloride type with high concentrations of silica, bicarbonate and sulfate. For organics, 50-70% of the organics present were phenols. However, organic compounds present in solution were only identified qualitatively using gas chromatograph.

A series of calculations were conducted to assess the interaction of waste waters with formation fluids for the McMurray and CBWA formations. The computer calculations were based on equilibrium conditions (i.e., kinetic effects not accounted for) and yield the concentration for aqueous species and the saturation index for minerals. The simulations are considered a preliminary screening step in assessing compatability of injected versus formation waters and are based on a number of assumed initial conditions. For instance, initial concentrations are assumed for silica, iron, aluminum and potassium leading to the question of the meaningfulness of the results. For instance, the most conclusive observation resulting from this effort is that amorphous silica will likely precipitate. However, the potential for precipitation of aluminosilicate minerals is not assessed due to its dependence on aluminum concentration and the suggestion of calcite precipitation is ignored without further explanation. This analysis is very preliminary in nature and need be reworked using representative formation water quality analyses with some assessment of kinetic effects on the trends suggested by equilibrium calculations.

An assessment of the partitioning behavior of selected waste waters was conducted using crushed samples of the McMurray and Beaverhill Lake Formations. Synthesized formation water was utilized and allowed to equilibrate to the crushed samples prior to introducing the phenol. Results indicated that "little difference could be found in the amount of activity in the water and organic fractions but that the Beaverhill Lake Formation sediments absorbed about an order of magnitude more activity than the McMurray Formation sediments". Also, kinetic effects were limited to a time frame amenable to laboratory partitioning studies. Further work is proposed in correlating lab and field studies to aid in the design of field testing programs.

In summary, this study is limited to a detailed discussion of only the CBWA with little information on other potential waste injection zones. Structure and isopach contour diagrams are quite

useful in terms of the current study but hydraulic parameters are too limited in number and areal coverage to be of great use. Also, studies conducted regarding waste water composition and phenol partitioning are preliminary in nature and require further study to quantify chemical concentrations and phenol and other organic chemical behavior.

2.1.2.2 Composition of Waste Water. Subsequent to submission of the Phase 1 and 2 reports, ARC continued with further work on their analyses of waste waters from a total of twelve oil sands and heavy oil pilot plants. Again, similar trends in water quality were observed between different pilot plant waste waters for analysis of both organic and inorganic parameters. Waste waters were analyzed by gas chromatograph/mass spectrometry but were only reported as to their fraction of mass relative to the species most abundant (i.e., no concentrations were reported).

2.1.2.3 Phenol Partitioning Between Sediment and Water Phases. A second part (Part 2) to the Phase 3 portion of the ARC/EC study involved further work on phenol partitioning. In this study, phenol partitioning was studied under a number of different conditions in terms of oxidizing/reducing conditions, solid/liquid ratios, formation total organic carbon and ionic strength. Partitioning coefficients were found (ARC, 1985d) to depend on solid/liquid ratio, formation lithology and ionic strength with little dependence on redox status and TOC. Kinetic effects were found to be of short duration during adsorption but likely of greater significance for desorption.

Retardation factors for phenol can be calculated for the partitioning coefficients reported utilizing an assumed bulk density of 2.75 and a reported porosity of 13% for the CBWA and 34% for the McMurray (ARC, 1985i). The range in retardation factors is 53 to 180 for the CBWA and 20 to 69 for the McMurray. The retardation factors can be interpreted by considering the velocity of phenol migration relative to that of the groundwater. Given that these retardation

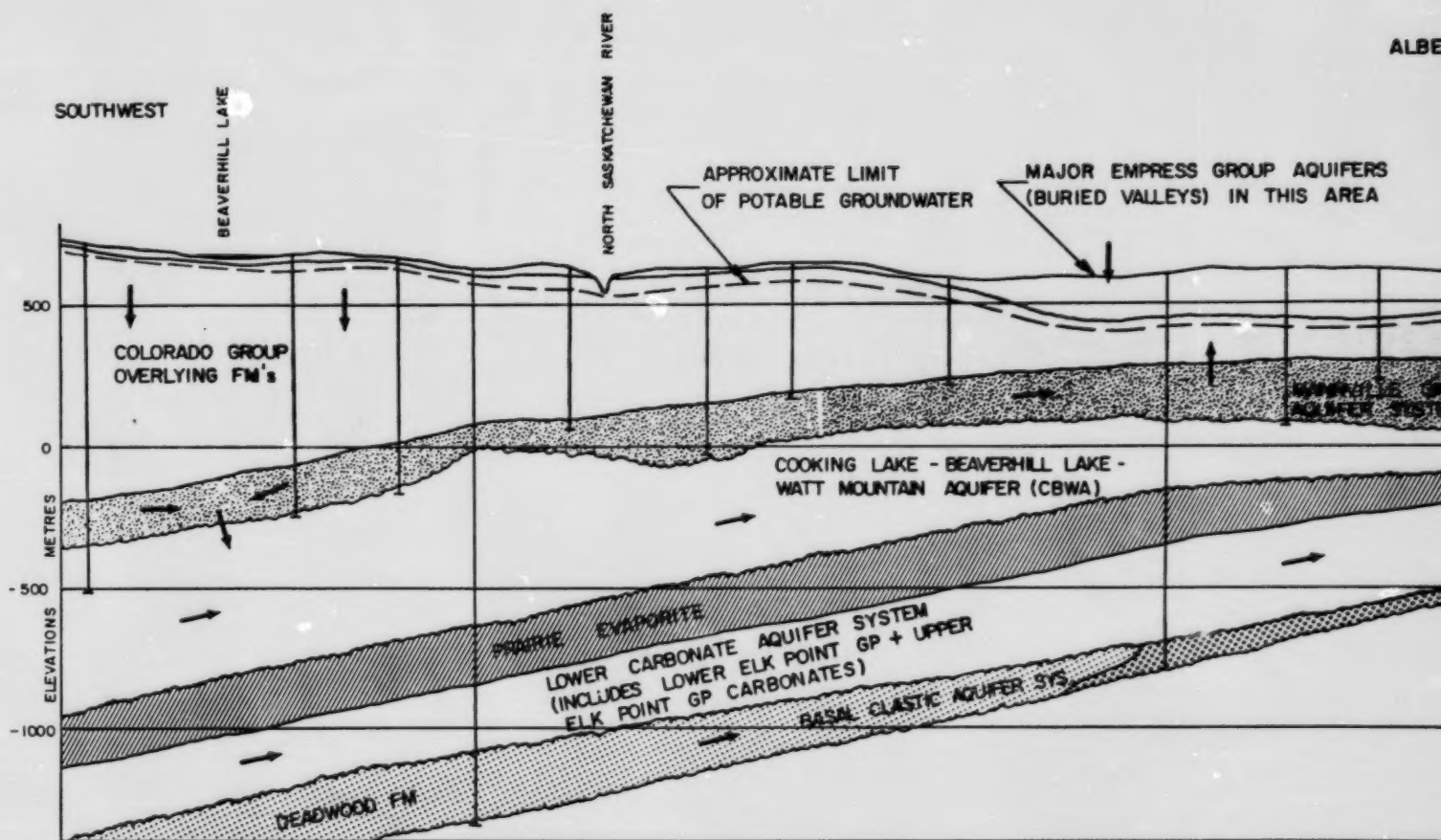
factors apply, phenols in the CBWA are likely to move 53 to 180 times slower than groundwater and phenols in the McMurray are likely to move 20 to 69 times slower than groundwater. Also, these retardation values only apply to phenols. The potential for migration of other parameters need be assessed relative to phenol retardation.

2.1.3 Meneley/Prairie Provinces Water Board Studies

W.A. Meneley Consultants Ltd. (1983a, 1983b) conducted a two part study commissioned by the Prairie Provinces Water Board (PPWB) aimed at identifying the potential effects on surface and subsurface water in both Alberta and Saskatchewan due to waste fluid disposal in the Cold Lake area. The results of these studies are summarized in the the following sections.

2.1.3.1 Preliminary Assessment of Existing Information. In this portion of the study, Meneley (1983a) reviews the geology and hydrogeology of the study area and discusses the potential waste injection zones and the conceivable impacts resulting from waste fluid injection.

In reviewing the properties of the Deadwood - Granite Wash Formation (Cambrian Age), Meneley (1983a) assigns this formation a high potential for waste fluid injection in the area south of the Meadow Lake Escarpment. To the north of the Escarpment, the formation begins to thin and becomes finer (see Figure 2.4) (with respect to grain size) such that it may "not have the continuity necessary for large scale fluid disposal". However, given the relatively low fluid injection rates which are currently occurring, this formation may be acceptable as an injection horizon.



NOTES

- 1 ARROWS INDICATE INFERRED GROUNDWATER FLOW DIRECTIONS
- 2 GEOLOGIC LOG USED IN DEVELOPING CROSS-SECTION

0

VERTICAL

FIGURE

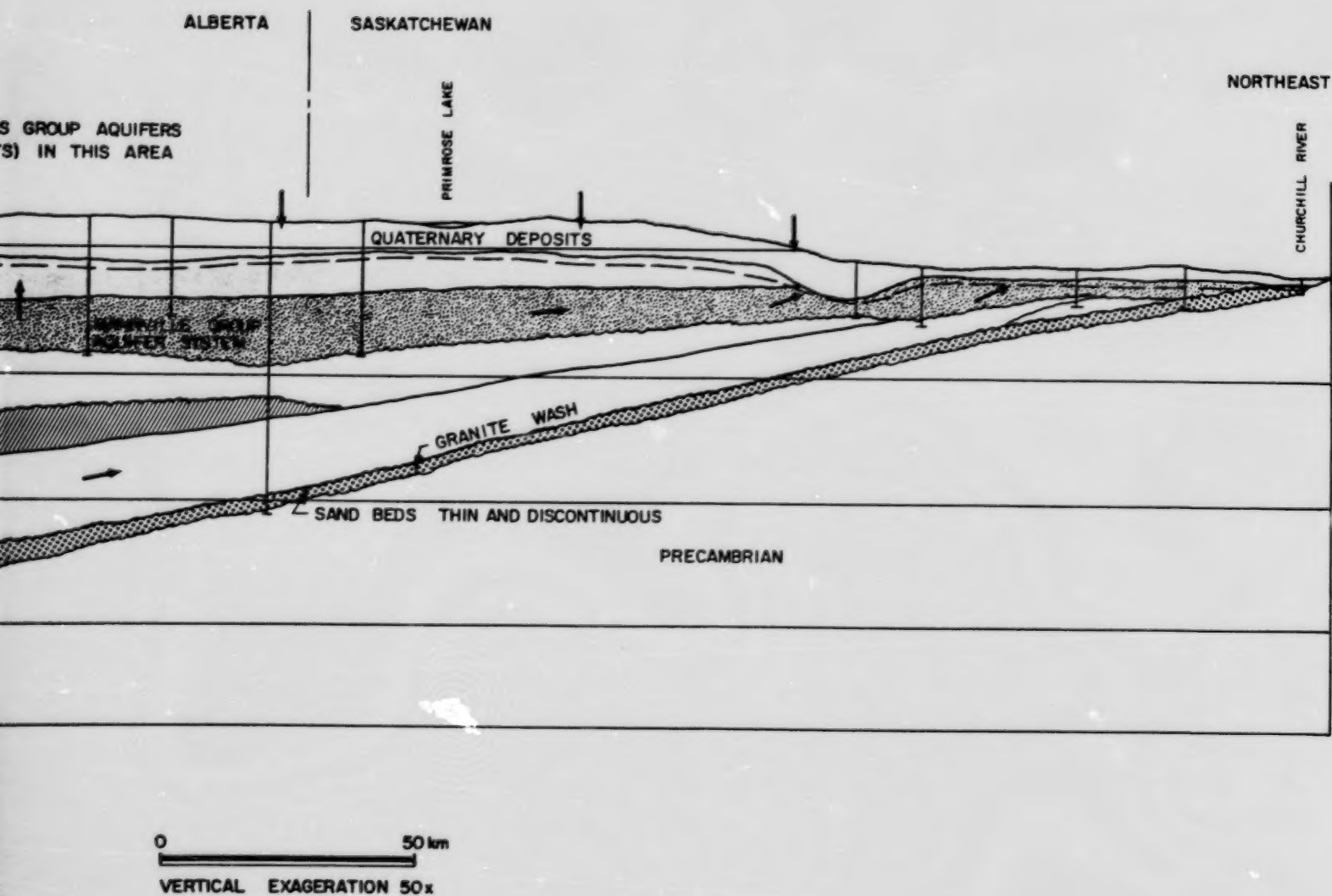


FIGURE 2-1 CROSS-SECTION SHOWING MAJOR HYDROSTRATIGRAPHIC UNITS
(After Meneley, 1983 a)

The Upper Elk Point Sub-Group, comprising the Keg River and Methy Formations in Alberta and the Winnipegosis Formation in Saskatchewan (Figure 2.1), may have a high capacity for waste fluid due to the presence of reefs (Meneley, 1983a). However, this is not confirmed. Also worth noting is the similarity in water quality to the underlying Granite Wash which raises the question as to the integrity of the confining units (Lotsburg and Cold Lake) between these two formations. These evaporite units are presumed to be confining layers but may be somewhat removed due to dissolution. The Cooking Lake - Beaverhill Lake - Watt Mountain aquifer (CBWA), also referred to as the Upper Carbonate Aquifer System or the Devonian, is likely confined below by the Prairie Formation (Salt) except where this evaporite is removed by solution in the eastern part of the study area (primarily Saskatchewan).

The Mannville Group is interconnected to the CBWA across the pre-Cretaceous Unconformity (PCU) in locations where the confining layers are absent (Figure 2.4). This formation/aquifer is thought to lie within the local groundwater flow system due to hydraulic head lows along the Battleford and Hatfield buried valleys. That is, a vertical connection may exist between the Mannville Group and the shallow groundwater system, possibly extending to the surface water system.

In the northeast portion of the study area, many of the confining units are absent resulting in a coalescence of aquifers into one hydrostratigraphic unit (Figure 2.4). Flow in this portion of the study area tends to be controlled by local topography with an overall flow direction to the northeast with discharge at the outcrop of the Canadian Shield.

Meneley also discusses the existence of relict groundwater flow systems which result from the time lag for re-equilibration of the regional groundwater flow system following major geologic events. In this particular area, recovery of the flow system following glaciation

and subsequent isostatic rebound may still be underway. The main point of the discussion is to postulate that the impact of subsurface waste injection may be to increase discharge of groundwater and that this groundwater may be relatively fresh due to recharge of these formations by fresh water below glaciers during the last glaciation. That is, increased groundwater discharge induced by subsurface injection pressures may not be highly saline and the water quality in existing discharge areas will not be substantially altered.

Meneley (1983a) performed calculations to estimate the radius of influence of one or more closely spaced injection wells for assumed conditions. The transmissivity, storage coefficient and flow rate values used were $1 \times 10^{-4} \text{ m}^2/\text{s}$, 1×10^{-3} and $1 \times 10^{-1} \text{ m}^3/\text{s}$ respectively. The aquifer model utilized for simulations was for a confined, non-leaky artesian aquifer for which the density and viscosity of the injected fluid were the same as the formation fluid. A simulation period of 10 years indicated that the radius of influence would be 10's of kilometres with head changes of 100 metres not being observed beyond 10 kilometres. It should be noted that the injection rates used are large compared to current operational values (ERCB, 1986, Appendix A; Figure 2.6). Meneley (1983a) concluded that further simulations were not justified until more definitive field information was collected. This included:

- hydraulic conductivities of the receiving zones;
- storativity;
- vertical and lateral hydraulic gradients;
- water chemistry of the formation and injection fluids.

2.1.3.2 The Impact of Heavy Oil Development in the Cold Lake Area on Groundwater in Saskatchewan. Meneley (1983b) conducts a quantitative analysis of historical waste fluid injection into the McMurray Formation for a situation analogous to that of the Esso operation near Cold Lake. The radius of influence, potential release scenarios and

potential environmental effects are discussed. A monitoring program is outlined in terms of well locations, construction details and monitoring methodology.

The main point of this report is that the pressure build-up due to waste fluid injection will likely be observed at 10's of kilometres distance and that release of waste fluids to overlying surface and subsurface waters may occur via a number of different release scenarios. These include upward flow through collapse structures related to solution of the Prairie Evaporites, microseismic events at less than two kilometres depth, glacial erosion of shale confining units overlying the McMurray, hydrodynamic blow-out structures created during glaciation and the anisotropies in the hydraulic properties of the McMurray due to its depositional environment. Meneley (1983b) concludes that "the present analysis serves to demonstrate that there are many factors which cannot be defined at this time. By ranging these factors it is possible to make the proposed waste water injection plan look as good or as bad as you wish".

A monitoring well network is proposed which includes wells completed in the McMurray and overlying formations located both near to the injection wells as well as at a distance in order to monitor pressure response and water quality in formations of concern. Furthermore, a number of remote sensing studies (i.e., photogrammetry and high resolution thermal infrared) are suggested in order to aid in identifying relevant structural features and alteration in groundwater discharge zones.

2.1.4 Private Industry Reports and Submissions to Provincial Regulatory Agencies

Subsequent to reviewing the primary studies which had been performed with regard to waste disposal, it readily became apparent that an up to date documentation of the nature and extent of waste disposal operations was not available. Furthermore, negligible hydrogeologic information had been collected for formations below the Cooking Lake - Beaverhill Lake - Watt Mountain Group in Alberta or for any of the Cretaceous or older strata in Saskatchewan. In order to develop a consistent and justifiable approach in evaluating the study area, it was necessary to fill these data gaps.

As a result of reviewing available studies dealing with the Cold Lake area geology, hydrogeology and hydrogeochemistry a number of areas of uncertainty were identified where further information was desirable. These include:

- Hydraulic parameters (hydraulic conductivities, permeabilities, porosities), hydraulic measurements (hydraulic heads) and hydrogeochemical analysis for formations below the Cooking Lake - Beaverhill Lake - Watt Mountain Formation aquifer (Upper Devonian). Studies by ARC (1985f) to date were limited to interpretation of hydrogeologic and hydrochemical information only above the Prairie Formation, yet 27 wells are reported to penetrate the top of the Prairie Formation and 18 reach the Precambrian. As a consequence, it is presumed that some data may exist for these formations which may affect their potential for consideration as an injection horizon.

Noteworthy points that needed to be addressed include:

- (i) Hydraulic properties and continuity of the Deadwood Formation - Granite Wash north of the Meadow Lake Escarpment.

- (ii) Hydraulic properties and continuity of the potential injection zones in reef complexes in the Elk Point and Methy Formations.
 - (iii) Hydraulic interconnection between the Deadwood Formation - Granite Wash and the Elk Point - Methy Formations (i.e., are the Lotsburg and Cold Lake intact and acting as aquitards).
-
- The studies available were limited only to the portion of the study area in Alberta - no information was presented for Saskatchewan. ARC is currently extending the existing data base to cover the Saskatchewan portion of the study area. Access to these studies was considered essential in developing a consistent and justifiable approach to selecting potential injection formations and test site locations.
 - Little information was available on existing deep well disposal operations. This information was important in identifying waste injection methodologies, formations, pressure build-ups, operational problems and environmental impacts. Furthermore, the expertise developed by operational personnel would likely provide valuable insight into the test methodology development and test site selection. The information of interest included injection rates, formation pressures, water quality, waste fluid/rock interactions, permeability and porosity of the injection formation and forecasted injection volumes.
 - Information on existing boreholes which is of sufficient detail to ascertain their utility in a test program. The information needed here, beyond what is present in the data base, is the current status of these candidate wells.

- Quantitative chemical analyses of waste injection fluids from pilot plants. Existing analyses are qualitative for many species. Quantitative analyses facilitate assessment of potential fluid/test equipment and formation/fluid incompatibilities.
- Well design and abandonment procedures.
- Oil industry criteria for injection wells (i.e., capacity, compatibility, proximity to pilot plants, proximity to source).
- Effective porosities of potential injection zone horizons. The existing database includes only porosities from core measurements which are likely matrix porosities and do not accurately reflect fracturing or dissolution. This is a significant factor particularly in carbonate reef complexes (i.e., Elk Point - Methy Formation).

The primary source for the information of interest was the government regulatory bodies at the provincial level. In Alberta, this is the Energy Resources Conservation Board (ERCB) and in Saskatchewan, the Saskatchewan Energy and Mines. Both of these agencies were approached early in the study with inquiries for the information identified. In Alberta, it was found that the most likely source of information regarding the hydraulic properties of the Middle Devonian and older formations was from recent disposal well applications as few wells penetrated these formations for reasons other than disposal. As a result, a data base search was initiated at the ERCB to initially identify the location of all disposal wells. At the same time, representatives of the oil companies were contacted to request assistance in acquiring information specific to their disposal wells and in identifying the current status of their disposal operations. ERCB (1986) provided a listing in which the well location, operator,

injection formation, top and base of perforated interval, cumulative injection volume, hours of injection and a calculated flow rate for all disposal wells in the study area. Details of the disposal wells are found in Appendix A. The disposal well locations are shown in Figure 2.5, with the injection formation indicated by symbol. The average injection rate reported by ERCB was calculated using the most up to date information for each disposal well. (Note: Some of the injection rates in Appendix A may be incorrect due to the fact that some operators consistently report the hours of disposal as 744 hours (31 day multiplied by 24 hours) regardless of actual disposal hours). However, the latest period of record was not the same for all wells. Regardless, the flow rates reported provide an indication of the current extent of waste disposal. To further summarize this information, flow rates were added for each formation within a township and are shown on Figure 2.6. This figure provides an indication of the areal extent and magnitude of waste injection. In Figure 2.5 and 2.6, it should be noted that the disposal wells west of approximately Range 12 are not affiliated with heavy oil production and are most likely used for produced water disposal originating from gas wells. This produced water likely consists primarily of brines and is not of as great a concern as the fluids disposed of following heavy oil extraction. For this reason, these disposal wells will not be considered as part of this study.

Additional hydraulic information was collected from selected disposal well applications on file with ERCB with the greatest emphasis placed on the wells completed in formations of Middle Devonian and greater age. This information is summarized in Table 2.1 to 2.3.

In Saskatchewan, inquiries with Saskatchewan Energy and Mines revealed that there are no disposal wells in the part of the province in which the current study area is located (Loseth, 1986). Furthermore, a very limited number of boreholes have been drilled in this area. A request was submitted for permeability and porosity data for all the Cretaceous and older strata within the bounds of the study area. A search was performed and identified 54 boreholes/wells for

ALBERTA

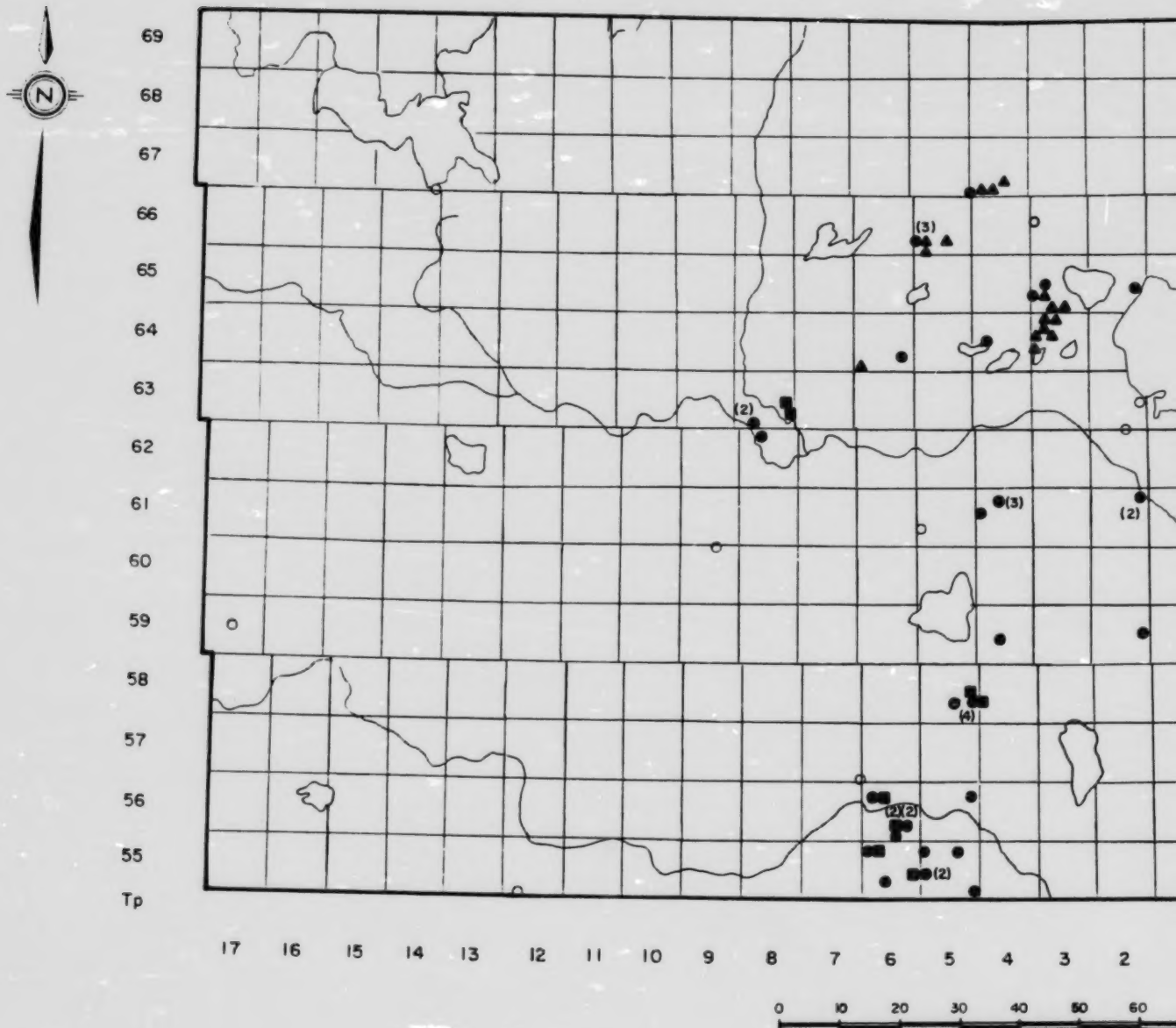
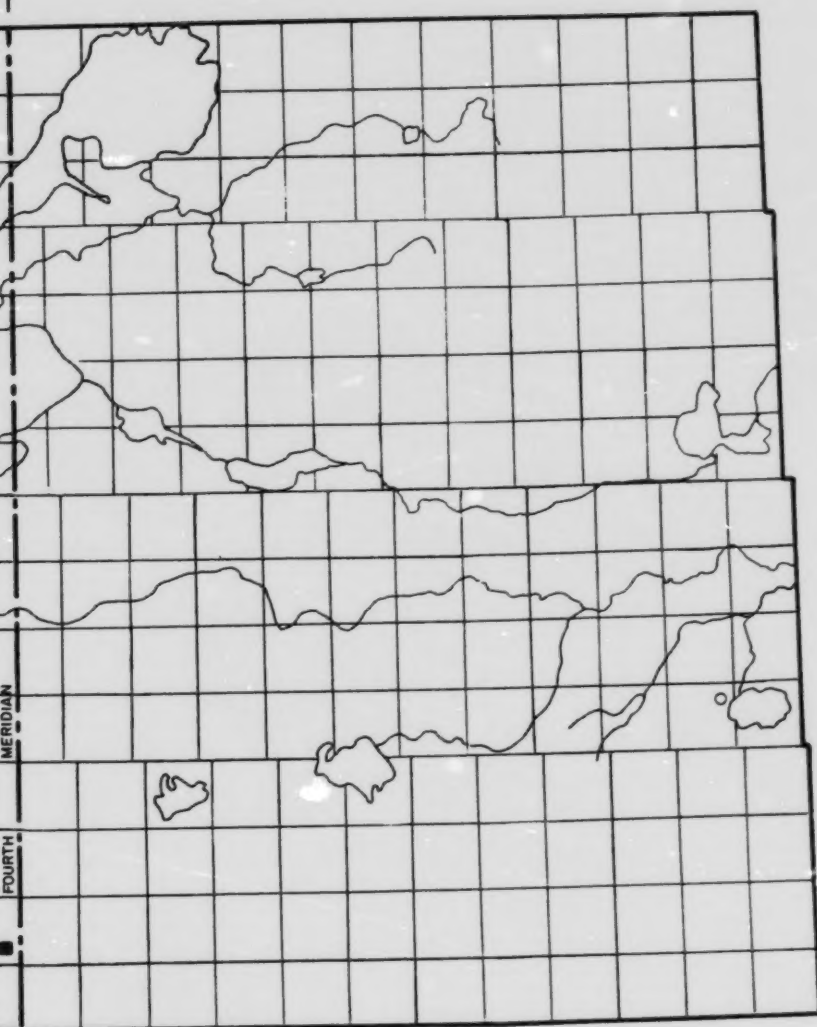


FIGURE 2-5 EXISTING OR PROPOSED SITES
(ERCB, 1986)

SASKATCHEWAN



LEGEND

- MANNVILLE GROUP
- COOKING LAKE -
BEAVERHILL LAKE -
WATT MOUNTAIN GROUP
- ▲ DEADWOOD / GRANITE
WASH
- UPPER DEVONIAN
(OTHER THAN CBWA)
- (2) NUMBER OF WELLS IN
A FORMATION/SECTION

27 26 25 24 23 22 21 20 19 18 17 16 Rg

70 80 90 100 km

SED DISPOSAL WELLS

ALBERTA

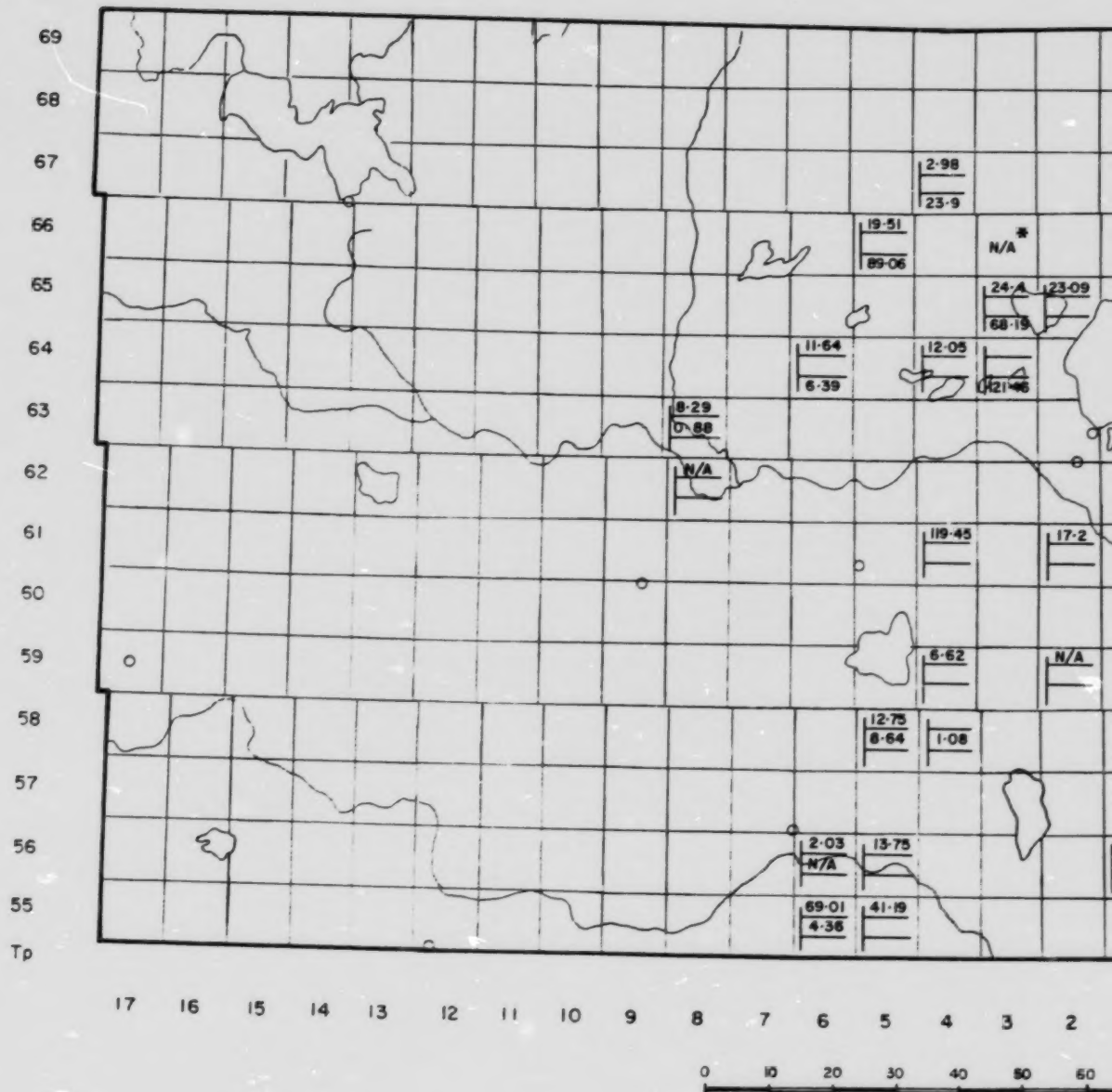


FIGURE 2-6 CUMULATIVE INJECTION
PER TOWNSHIP FOR
(From ERCB, 1980)

SASKATCHEWAN

LEGEND

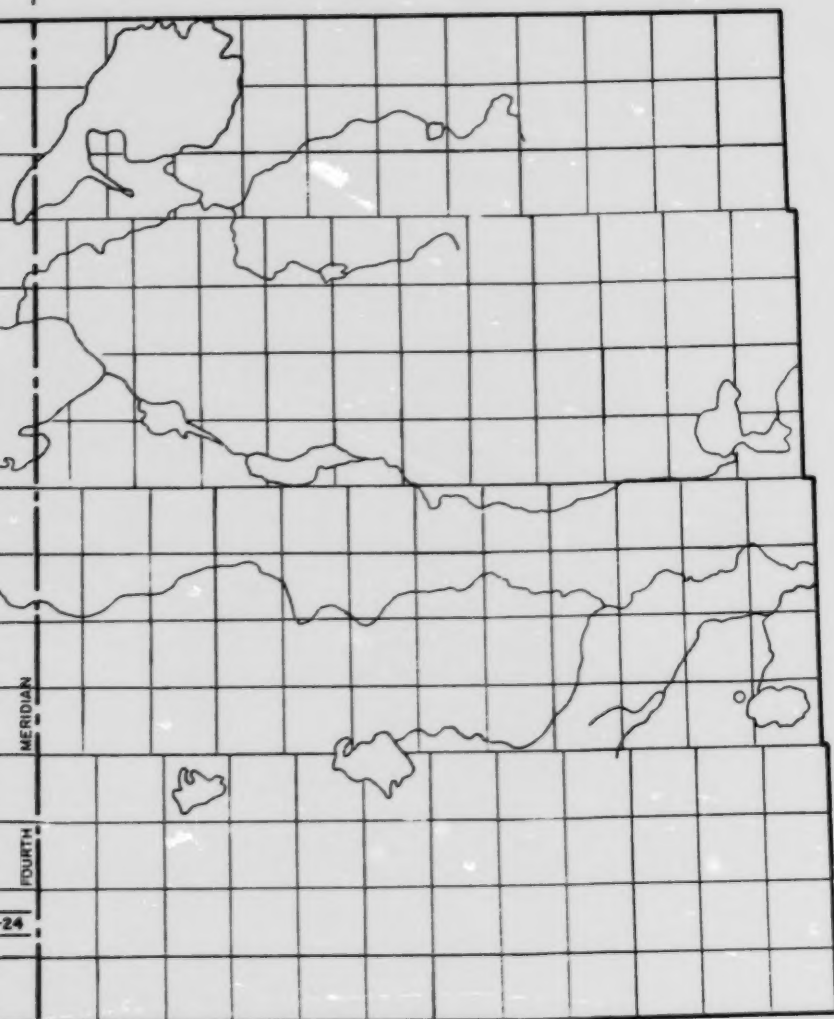
MANNVILLE GROUP
LOWER CRETACEOUS

CBWA

CAMBRIAN/GRANITE WASH

* UPPER DEVONIAN
OTHER THAN CBWA

N/A FLOW RATE
NOT AVAILABLE



ION RATES
EACH FORMATION (m^3/hr)

Table 2.1 Hydraulic Properties for the Mannville Group in Alberta

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Thickness		Well Operator/ Reference
		(as reported)	(m ²)	No. of Values	%	Formation	Injection Interval	
Clearwater	13-20-62-3	1.5 d (approx.)	1.5E-12	n/a	32	n/a	9.8	Drummond (1986)
Clearwater	9-28-55-6	n/a	n/a	n/a	31.5 (avg.)	26	28	Amoco (1984a)
McMurray	10-24-59-2	n/a	n/a	n/a	30 (avg.)	10	n/a	Amoco (1985a)
McMurray	Tp55-69, Rq1-17	6.5E-13 m ² (median hor'l)	6.5E-13	72	n/a	n/a	n/a	ARC (19851)
McMurray	Tp55-69, Rq1-17	4.6E-14 m ² (median ver'l)	4.6E-14	10	n/a	n/a	n/a	ARC (19851)
McMurray	Tp55-69, Rq1-17	1.1E-14 m ² (DST)	1.1E-14	52	n/a	n/a	n/a	ARC (19851)
Lower Mannville above McMurray	Tp55-69, Rq1-17	1.0E-14 m ² (median hor'l)	1.0E-14	146	n/a	n/a	n/a	ARC (19851)
Lower Mannville	Tp55-69, Rq1-17	2.7E-14 m ² (median hor'l)	2.7E-14	15	n/a	n/a	n/a	ARC (19851)
Lower Mannville	Tp55-69, Rq1-17	1.0E-14 m ² (DST)	1.0E-14	66	n/a	n/a	n/a	ARC (19851)
Upper Mannville	Tp55-69, Rq1-15	1.3E-14 m ² (median hor'l)	1.3E-14	333	33	n/a	n/a	ARC (19851)
Upper Mannville	Tp55-69, Rq1-15	2.3E-13 m ² (median ver'l)	2.3E-13	14	33	n/a	n/a	ARC (19851)
Upper Mannville	Tp55-69, Rq1-15	1.3E-14 m ² (DST)	1.3E-14	333	33	n/a	n/a	ARC (19851)

Note: (1) All values are derived from core analysis except where noted
(2) All permeabilities are horizontal except where noted --

Table 2.1 Hydraulic Properties for the Mannville Group in Alberta (cont'd)

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Thickness		Well Operator/ Reference
		(as reported)	(μ^2)	No. of Values	%	Formation	Injection Interval	
Cleerwater	6-11-64-6	1500 md	1.5E-12	n/a	30	35	8	Mobil (1982)
Lloydminster	10-9-55-6	n/a	n/a	n/a	32	20	15	Pan Canadian (1983)
Lloydminster	11-3-56-6	n/a	n/a	n/a	33	26	25	Pan Canadian (1985)
Cummings	5-28-61-4	13 md	1.3E-14	n/a	n/a	n/a	n/a	Suncor (1985)
Cummings	2-28-61-4	1430 md	1.4E-12	n/a	n/a	n/a	n/a	Suncor (1985)
McMurray	6-11-64-6	2-3 d	2.0E-12	n/a	35	n/a	n/a	Mobil (1985b)
McMurray	12-28-64-4	GT 500 md	GT 4.9E-13	n/a	35	50-70	12.8	Husky (1983a)
Rex	10 & 11-56-6	1.0 (μm) ²	1.0E-12	n/a	32.5	22.5 (avg.)	10	Dome (1985a)
Rex	6-27-55-5	500 md (estimated)	4.9E-13	n/a	34 (density log)	25	4	Westmin (undated)

Note: (1) All values are derived from core analysis except where noted
 (2) All permeabilities are horizontal except where noted
 (3) GT = greater than

Table 2.2 Hydraulic Properties for the Upper Devonian Group in Alberta

Formation/ Number	Well I.D./ Location	Permeability		Porosity		Thickness		Well Operator/ Reference
		(as reported)	(m ²)	No. of Values	%	Formation	Injection Interval	
Beaverhill Lake Group	n/a	n/a	n/a	n/a	13-14	n/a	n/a	BP (1985b)
Cooking Lake	13-58-5	n/a	n/a	n/a	15	n/a	21	Murphy (1985a)
CBWA	Tp55-69, Rq1-17	8.4E-14 m ² (median hor'l)	8.4E-14	29	13	n/a	n/a	ARC (1985i)
CBWA	Tp55-69, Rq1-17	4.5E-16 m ² (median vert'l)	4.5E-16	12	13	n/a	n/a	ARC (1985i)
CBWA	Tp55-69, Rq1-17	3.5E-15 m ² (DST)	3.5E-15	4	n/a	n/a	n/a	ARC (1985i)
Cooking Lake	7-28-55-6	n/a	n/a	n/a	13-18	45	n/a	Amoco (1984b)
Ireton	10-7-55-6	n/a	n/a	n/a	15-18	n/a	n/a	Amoco (1984b)
Ireton	11-22-55-6	n/a	n/a	n/a	6 (avg.)	n/a	n/a	Amoco (1984b)
Ireton	6-33-55-6	n/a	n/a	n/a	8 (avg.) 5-8	n/a	n/a	Amoco (1984b)
Cooking Lake	12-33-55-9	0.41-8.50 *	4.0E-13 - 8.4E-12	5	9.3-16.1	54	n/a	Amoco (1984b)
Cooking Lake	12-33-55-9	0.01-2.70 *	9.9E-15 - 2.7E-12	5	9.3-16.1	54	n/a	Amoco (1984b)
Cooking Lake	6-13-63-8	n/a	n/a	n/a	15-18	n/a	22	Canadian Occidental (1985a)
Cooking Lake	10-12-63-8	n/a	n/a	n/a	n/a	n/a	9.5	Canadian Occidental (1985a)

Notes: (1) All values are derived from core analysis except where noted
 (2) All permeabilities are horizontal except where noted
 (3) GT = greater than
 (4) * means no units; d assumed

Table 2.2 Hydraulic Properties for the Upper Devonian Group in Alberta (cont'd)

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Thickness		Well Operator/ Reference
		(as reported)	(m ²)	No. of Values	%	No. of Values	Formation Interval	
Cooking Lake	10 & 11-56-6	n/a	n/a	n/a	13-18	n/a	45	Dome (1985a)
Grosmont	11-3-69-16	LT 700 md	LT 6.9E-13	n/a	24 (avg.)	n/a	61	Novalta (1977)

Note: (1) All values are derived from core analysis except where noted
 (2) All permeabilities are horizontal except where noted
 (3) GT = greater than
 (4) LT = less than

Table 2.3 Hydraulic Properties for the Cambrian/Granite Wash in Alberta

Formation/ Number	Well I.D./ Location	Permeability		Porosity		Thickness		Well Operator/ Reference
		(as reported)	(m ²)	%	No. of Values	Formation	Injection Interval	
Granite Wash	11 & 9-8-66-5	0.04-2.0 (um) ²	4.0E-14 - 2.0E-12	20-25	n/a	30-40	n/a	BP (1983a)
Granite Wash	16-4-67-4	2000 (Mm ²)	n/a	20	n/a	25	n/a	Dome (1985b)
Granite Wash	10-10-67-4	1-2 d	1.0E-12 - 2.0E-12	20	n/a	n/a	n/a	Dome (1985c)
Granite Wash	10-10-67-4	n/a	n/a	25 (avg.)	n/a	n/a	n/a	Mobil (1985a)
Granite Wash	n/a	n/a	n/a	15-26	n/a	n/a	n/a	Mobil (1985a)
Granite Wash	12-6-64-6	150-200 md	1.5E-13 - 2.0E-13	21	n/a	n/a	15	Mobil (1985a)
Granite Wash	12-8-65-3	643-3178 md (hor'l)	6.3E-13 - 3.1E-12	12.7-25.8	n/a	52	20	Esso (1985a)
Granite Wash	12-8-65-3	643-3178 md (hor'l)	6.3E-13 - 3.1E-12	16.7 (mean)	n/a	52	20	Esso (1985a)
Dolomite (overlying Granite Wash)	12-8-65-3	n/a	n/a	4	n/a	39	n/a	Esso (1985a)
Granite Wash	7-18-64-3	1.79-9150 md	1.8E-15 - 9.0E-12	n/a	n/a	64	20	Esso (1985a)
Granite Wash	11-22-64-3	LT 0.01 - 12,500 md	9.9E-18 - 1.2E-11	9-28.7	136	87	n/a	Esso (1985a)

Notes: (1) All values are derived from core analysis except where noted
 (2) All permeabilities are horizontal except where noted
 (3) GI = greater than
 (4) LT = less than

which some or all of the above information existed. Again, there is a relative paucity of data for the formations of pre-Cretaceous age. This information has been summarized in Tables 2.4 through 2.6.

The Standards and Approvals Branch of Alberta Environment was also contacted with regards to water quality records for the waste water produced by the in situ heavy oil extraction plants. These water quality analyses involve the analytical results for several indicator parameters including pH, oil and grease, COD, TDS, phenols, sulphides, chloride sodium and potassium. The water samples were collected from eleven operations within the study area (Primus, 1986) (Table 2.7).

Alberta Environment was also able to provide deep well disposal volumes on an annual basis for 45 disposal wells in Alberta (Primus, 1986). The fluids disposed include all produced water below 600 metres and all industrial waste water.

Subsequent to collecting additional information from these various sources, it seems that there still exists a distinct bias in the coverage of borehole data. The majority of information is concentrated in the heavy oil areas and does not extend much below the Lower Cretaceous age producing horizons or into Saskatchewan. Very little information exists to characterize the hydrogeology in Saskatchewan with somewhat more but still limited information found regarding the Middle Devonian and older formations in Alberta.

The hydrogeologic information obtained originates with the oil industry or other mineral extraction sectors. The data obtained are primarily permeabilities (to air) and porosities from measurements performed on cores. No in situ testing results (i.e., DST's) were analyzed for permeability values other than the values reported in the ARC studies. The porosity values obtained from core samples are likely reliable indicators of effective matrix porosity. That is, the testing method used, which is typically the Double-Cell Method (API, 1960), is

Table 2.4 Hydraulic Properties for the Mannville Group in Saskatchewan

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Formation Thickness (m)	Well Operator/ Reference	
		(as reported)	(m ²)	No. of Values	%			
n/a	01-01-10-66-27-3	13.18-1600 md	1.3E-14 - 1.6E-12	33	27.4-40.2	40	262	Core Laboratories (1969a)
McLaren	61-13-27-60-27-3	n/a	n/a	n/a	27.2-46.8	8	23	Core Laboratories (1969b)
Dina	01-12-20-56-27-3	n/a	n/a	n/a	23.1-39.4	3	46	Core Laboratories (1965a)
Dina	21-06-28-56-27-3	996-2700 md	9.8E-13 - 2.7E-12	5	25.2-34.3	15	52	Core Laboratories (1980a)
Dina	01-04-08-56-27-3	2.99-10,240 md	3.0E-15 - 1.0E-11	n/a	0.0-46.0	n/a	44	Core Laboratories (1984a)
		(5148 md avg.)	5.1E-12		(32.2 avg.)			
Cummings	21-06-20-55-27-3	101-712 md	1.0E-13 - 7.0E-13	7	25.5-30.9	14	25	Core Laboratories (1981a)
Cummings	01-07-09-55-27-3	n/a	n/a	n/a	22.5-24.6	2	29	Core Laboratories (1981b)
Dina	01-07-09-55-27-3	n/a	n/a	n/a	30.2-35.3	14	25	Core Laboratories (1981b)
n/a	01-15-34-65-26-3	293.77 md avg.	2.9E-13	n/a	34.26 avg.	n/a	262	Core Laboratories (1969c)
Colony	11-05-26-61-26-3	4-1905 md	3.9E-15 - 1.9E-12	38	32.1-33.1	3	29	Geotech (1983a)
Colony	31-06-11-61-26-3	3-184-md	3.0E-15 - 1.8E-13	12	16.9-32.0	13	25	Geotech (1983b)
n/a	01-13-31-62-25-3	66.00-1530.00 md	6.5E-14 - 1.5E-12	11	28.3-48.0	11	n/a	Core Laboratories (1969d)
n/a	11-10-24-64-19-3	173.00-595.00 md	1.7E-13 - 5.9E-13	3	40.0-40.6	5	609	Core Laboratories (1972)

Table 2.5 Hydraulic Properties for the Middle Devonian in Saskatchewan

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Formation Thickness (m)	Well Operator/ Reference
		(as reported)	(m ²)	%	No. of Values		
Winnipegosis	01-01-10-66-27-3	n/a	n/a	22.4-32.2	7	45	Core Laboratories (1969a)
Winnipegosis	31-14-17-65-26-3	0.05-272.69 md	4.9E-17 - 2.7E-13	2.60-26.6	43	45	Core Laboratories (1968a)

Table 2.6 Hydraulic Properties for the Cambrian in Saskatchewan

Formation/ Member	Well I.D./ Location	Permeability		Porosity		Formation Thickness (m)	Well Operator/ Reference
		(as reported)	(m ²)	No. of Values	%	No. of Values	
Deadwood	01-08-11-62-22-3	133-839 md (radial)	1.3E-13 - 8.3E-13	2	13.1-29.2	2	Chemical and Geological Laboratories (1957)
Deadwood	01-08-11-62-22-3	145-216 md (vertical)	1.4E-13 - 2.1E-13	2	n/a	n/a	Chemical and Geological Laboratories (1957)

Table 2.7 Water Quality Analysis from In Situ Heavy Oil Recovery Schemes (Primus, 1986)

Operator	Location	Well I.D. (W4M)	Depth of Injection (m)	Year	pH	CO ₂ (ppm)	TDS (ppm)	Oil & Grease (ppm)	Phenols (ppm)	Sulphide (ppm)	Chloride (ppm)	Sodium (ppm)	Potassium (ppm)
Amoco	St. Line	2-4-63-8 13-33-62-8	409-413	1980	7.8	-	17728.0	9.0	0.4	0.01	8255.0	4817.0	73.8
BP	Marguerite Lake	8-7-66-5	422-440	1979	7.7	1075.0	7096.0	229.0	7.0	0.3	-	-	-
				1980	7.8	1092.0	7044.0	127.0	73.8	1.0	-	-	-
				1981	7.5	1785.0	8232.0	125.1	6.1	1.8	-	-	-
				1982	8.0	957.0	6081.0	114.4	2.3	0.05	-	-	-
Chevron	Beaver Crossing	5-31-61-1 12-31-61-1	408-418	1981	7.3	4525.0	8898.0	35.2	23.9	0.2	5370.0	-	-
				1982	7.5	1082.0	8377.0	267.0	4.7	0.05	4862.0	-	-
				1983	7.4	206.0	6920.0	43.4	2.8	0.05	3855.0	-	-
				1984	7.4	789.0	6151.0	106.0	3.7	17.0	3443.0	-	-
				-	-	-	-	-	-	-	-	-	-
Dome	Lindbergh	14-18-55-5 10-18-55-5 3-30-55-5 6-24-55-5 11-24-55-5	542-547 540-545 548-554 535-545 650-665	1980	7.4	-	52449.0	-	-	-	-	-	-
				1981	7.0	-	-	-	-	-	-	-	-
				1984	8.8	-	-	201.3	78.1	0.05	-	-	-
				-	-	-	-	-	-	-	-	-	-
Esso	Leming	1-8-65-3	1270	1980	7.0	2112.0	4798.0	518.0	10.9	-	2401.0	-	-
				1981	7.1	863.0	5115.0	56.8	8.8	-	2740.0	-	-
				1982	7.6	1870.0	7400.0	13.4	8.4	-	2755.0	-	-
				-	-	-	-	-	-	-	-	-	-
Mobil	Primrose	-	-	1982	7.6	-	25275.0	-	-	-	14910.0	5021.0	43.5
Petro- Canada	Muriel Lake	-	-	1982	7.0	-	17500.0	-	-	-	292.9	254.1	-
				-	-	-	-	-	-	-	-	-	-
Westmin	Lindbergh	13-55-6	-	1982	7.4	-	67600.0	-	-	-	41500.0	21700.0	129.0

indicative of the porosity of the interconnected voids. This method reflects the matrix porosity as the samples used in core analysis are relatively unfractured. In particular, fracture zones or dissolution zones present in the formation are not reflected in the porosities from core analysis due to poor recovery in these zones. As a result, core porosities are typically an underestimate of in situ effective porosities.

Similar scale effects are present in permeability values reported from core analysis. These permeability values are likely indicative of matrix permeabilities and do not account for fractures and/or bedding planes which may account for the greatest component of the bulk or overall permeability. This is of particular concern in low matrix permeability formations (i.e., shales) where the matrix component of the overall permeability is quite low. As a consequence, the available lab measured hydraulic parameters are likely not indicative of in situ values.

2.1.5 Regulatory Requirements for Disposal Operations

The regulations governing waste fluid disposal by injection were reviewed primarily to ascertain what information could be expected to be found on file with the regulatory agencies. In addition, the regulatory requirements provide insight to the disposal operations within a jurisdiction as well as to some of the problems which may be related to waste fluid injection. Disposal well completion and abandonment requirements are two such areas of concern.

In Alberta, the Energy Resources Conservation Board (ERCB) is the primary agency governing waste fluid injection with some limited involvement by Alberta Environment. The requirements are stated in Section 26, clause (c) of the Oil and Gas Conservation Act and Oil and Gas Conservation Regulations (ERCB, 1984). The information required by the Board in a disposal well application is stated as follows in

ERCB (1984):

- (a) maps showing:
 - (i) the location of the disposal well;
 - (ii) the lessors and lessees within 3 kilometres of the proposed disposal well;
 - (iii) status of each well adjacent to the disposal well, and
 - (iv) the structure or isopachs of the pool into which fluids will be disposed;
- (b) figures showing:
 - (i) geological cross-sections including the top and base of the formation, water-oil, gas-oil, and gas-water interfaces;
 - (ii) completion details of the proposed disposal well including:
 - (A) the depth of the packer,
 - (B) existing completion interval and the proposed disposal interval, and
 - (C) the inhibited fluid to be used in the annulus, and
 - (iii) the measurement and water handling facilities;
- (c) a tabulation of:
 - (i) reservoir parameters including vertical and horizontal permeabilities, aquifer and pool thicknesses;
 - (ii) the virgin reservoir pressure, bubble point pressure, current reservoir pressure, pressure gradients and the rate of pressure decline;

- (iii) the results of the material balance calculations including anticipated interface movements, and drive indices;
- (iv) pool production history; and
- (v) production history of the disposal well and each of the wells in the first two rows offsetting it showing water-oil ratios; and
- (d) discussion of the stratification within the pool to indicate whether a limitation of the disposal rate is necessary to protect offset wells and to achieve the maximum recovery of oil and gas.

Additional requirements set out by the Board in Information Letter IL-84-12 but not mentioned specifically in the Act and Regulations include surface casing and logging requirements. Surface casing is required to a minimum of 180 metres deep to reduce the possibility for contamination of potable ground waters due to casing failures, zonal communication or otherwise inadequate well completions. Further to this cause, cement bond, cement evaluation and casing inspection logs are required in all wells proposed for disposal. There also exists a number of ongoing monitoring requirements which include:

- annual test of packer seal;
- monthly injection volumes and duration of injection;
- maximum monthly well head pressure (reported monthly);
- annulus pressure (reported monthly).

Some problems have been encountered with casing failures in the enhanced recovery heavy oil extraction horizons due to heat stress on the casing. Additional regulations now require the use of thermal cement through these high temperature zones. This requirement has been in place for approximately one and a half years (Davis, 1986).

In addition, Alberta Environment requests that continuous well head pressure and flow rate records be submitted along with analysis of pH, total organic carbon and total dissolved solids from grab samples collected every three months. These measurements are reported in an annual submission to the Director, Standards and Approvals Branch.

In terms of ERCB requirements for disposal well abandonment, it is reported that a bridge plug must be placed within the production tubing just above the perforations. Then a minimum of 8 m of cement are placed above the plug following pressure testing (Schmidt, 1986). The production tubing is filled with a corrosion inhibiting fluid and cut off and sealed with cement at 1 m below ground surface.

Further ERCB requirements exist which are not necessarily related to disposal wells but are of interest with regards to developing monitoring facilities including the regulations regarding casing of wells. It is reported (Davis, 1986) that following drilling a drill rig cannot be moved from the borehole until either a casing is installed or the well is cemented. That is, no uncased holes exist for use as a monitoring well with the exception of core holes (which can be left uncased) and plugged holes. Re-entry of plugged holes is reported to be relatively unsuccessful (Zenon, 1983). Only cased holes exist. Cased holes must be recompleted in the zone of interest by perforating the casing. This has a number of implications regarding geochemical sampling and hydraulic testing and is discussed in detail in a subsequent chapter. In recently drilled dry holes, which are uncased, abandonment requirements are that cement plugs be placed to isolate zones with porosity (Schmidt, 1986).

The Saskatchewan Energy and Mines (SEM) regulates disposal operations by injection within Saskatchewan. The regulations are specified in Section 5.2 of the Oil and Gas Conservation Act for which a consolidated version is available (SEM, 1985). These regulations pertain primarily to salt water disposal wells with no provisions for other fluids. Guidelines for application for a salt water disposal well suggest that the following technical information should be included in an application (SEM, 1985):

- (a) location and co-ordinates of the proposed disposal well;
- (b) history of the well if such well is to be recompleted or converted. This should include all perforations, cement squeezes, workovers, etc., presented chronologically from the finish drilling date to the time of the application;
- (c) general discussion of the geology in the vicinity of the proposed disposal well, along with a geological cross-section of the pool including the well in question, highlighting the injection formation and the associated oil-water contact, porosity, permeability, drill stem tests, perforations, etc.;
- (d) a contour map of the top of the injection zone showing oil and gas wells and dry holes in the vicinity of the proposed injection well;
- (e) depth and thickness of the zone within the formation into which the water is to be injected;

- (f) the cumulative and latest average rate of production of oil, water and gas from all produced zones in the subject well;
- (g) a discussion of the zone(s) from which wells in the area are producing or have produced, giving the reservoir characteristics of the zone(s) and the production history, if any, of surrounding wells from the injection formation;
- (h) general discussion of completion practice with respect to producing wells in the area;
- (i) casing description and completion method for the proposed disposal well, including all required cement squeezes, new perforations, depth packer is to be set at, tubing-casing annulus conditions, etc.;
- (j) proposed internal and external corrosion protection for the entire surface and subsurface disposal system;
- (k) a diagrammatic sketch or sketches showing surface equipment, including well-head, piping arrangement, method of cleaning or chemical treatment of salt water, together with the method of measuring water for disposal;
- (l) description of the fluid to be injected, including its origin, estimated total daily amount to be injected, along with proposed injection pressure required, and other information incidental to the fluid being disposed of;

- (m) an indication of whether the injection well is to be used by parties other than the applicant;
- (n) such further information as the department may require.

Long term monitoring requirements include the submission of volume and pressure records along with water quality analysis. These requirements are partially the responsibility of Saskatchewan Environment.

It should also be noted that a study is currently under way in Saskatchewan to evaluate disposal regulations regarding hazardous liquid waste disposal by deep injection. The study is being performed by a private sector consultant (M.M. Dillon Ltd.) for Saskatchewan Environment. The results of this study could alter the disposal well requirements if the recommendations of the study are adopted by the Saskatchewan government.

Contact with Saskatchewan Energy and Mines have found that no disposal wells exist within the study area portion of Saskatchewan (Loeth, 1986).

2.2 PROBLEM ASSESSMENT

Through an evaluation of existing reports and studies and discussions with industry and government representatives, a number of issues have been identified which may potentially affect the extent of waste fluid migration. These issues are discussed in the following sections.

2.2.1 Potential Environmental Impacts

2.2.1.1 Meadow Lake Escarpment. The Meadow Lake Escarpment was formed in Early Devonian times due to erosion of Cambrian age formations by seas encroaching from the north. Within the study area, the resistant Ordovician formations were removed leading to extensive erosion of the primarily clastic Cambrian formations. An escarpment was formed which reached a maximum of 250 m in height and was a major controlling factor in deposition of the Middle Devonian formations (ARC, 1985g). The approximate alignment of the escarpment is shown in Figure 2.7.

It should be noted that some discrepancies exist in referring to the Cambrian age formation as described in Pugh (1971). Meneley (1983) refers to the entire Cambrian age sequence as either the Deadwood Formation, the Granite Wash or the Basal Clastic Aquifer System. On the other hand, Pugh (1971) refers to the Deadwood Formation and Basal Sandstone as separate units both of which comprise part of the Cambrian along with several other formations. In this report, the entire Cambrian will be treated collectively and will be referred to as the Cambrian/Granite Wash.

The Deadwood Formation of Upper Cambrian age is described as "succession of largely fine-grained clastic rocks between the top of the Pika Formation at the Middle Cambrian - Upper Cambrian boundary and the Cambrian - Ordovician unconformity" (Pugh, 1971). The Basal Sandstone (Pugh, 1971) is described as "mainly coarse-grained sandstones lying unconformably on Precambrian igneous and metamorphic rocks" composed of "rounded and poorly to very poorly sorted quartz grains". The Basal sandstone of Pugh (1971) varies in thickness from 250 to 300 feet throughout the study area (within Alberta) although

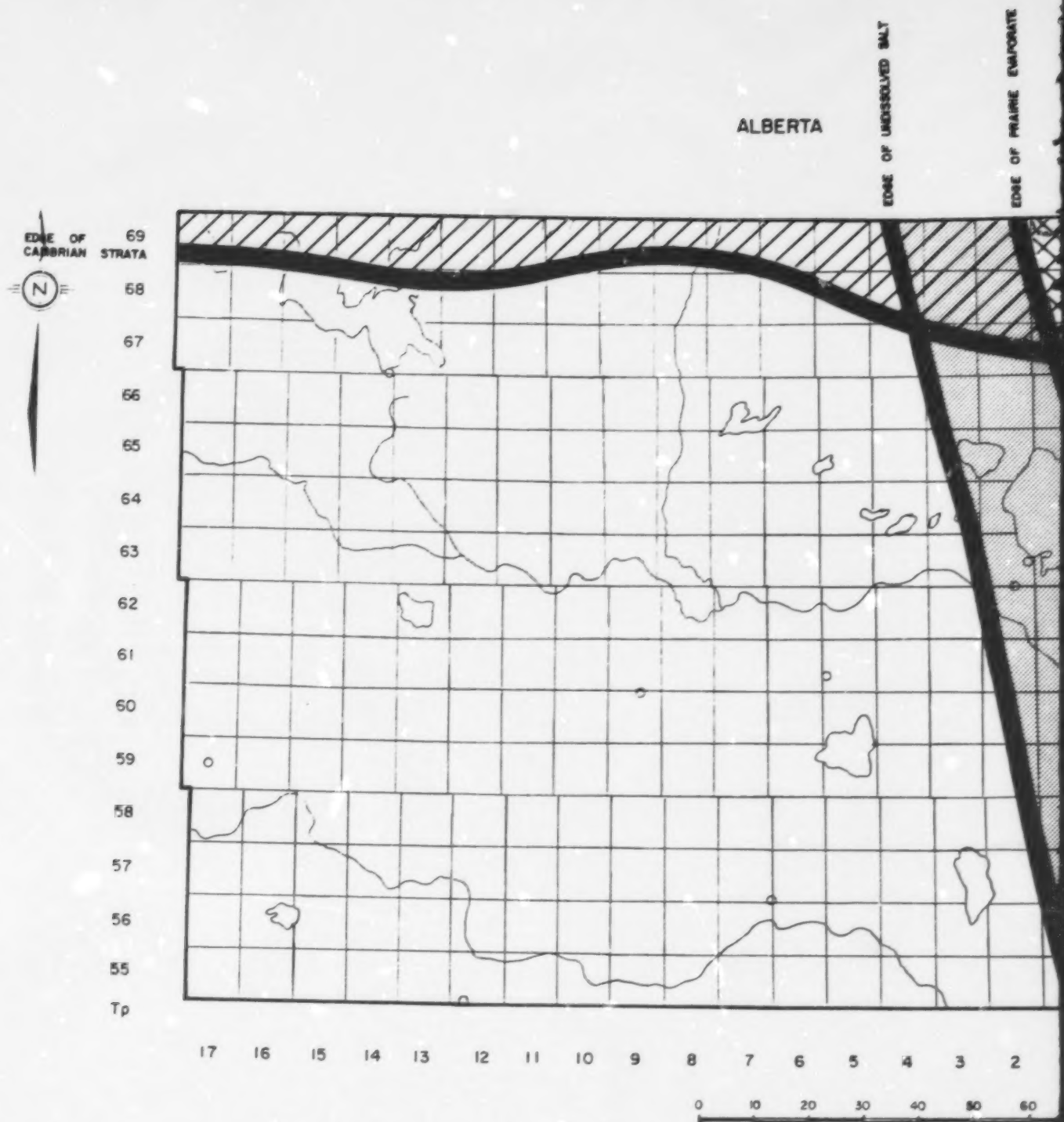


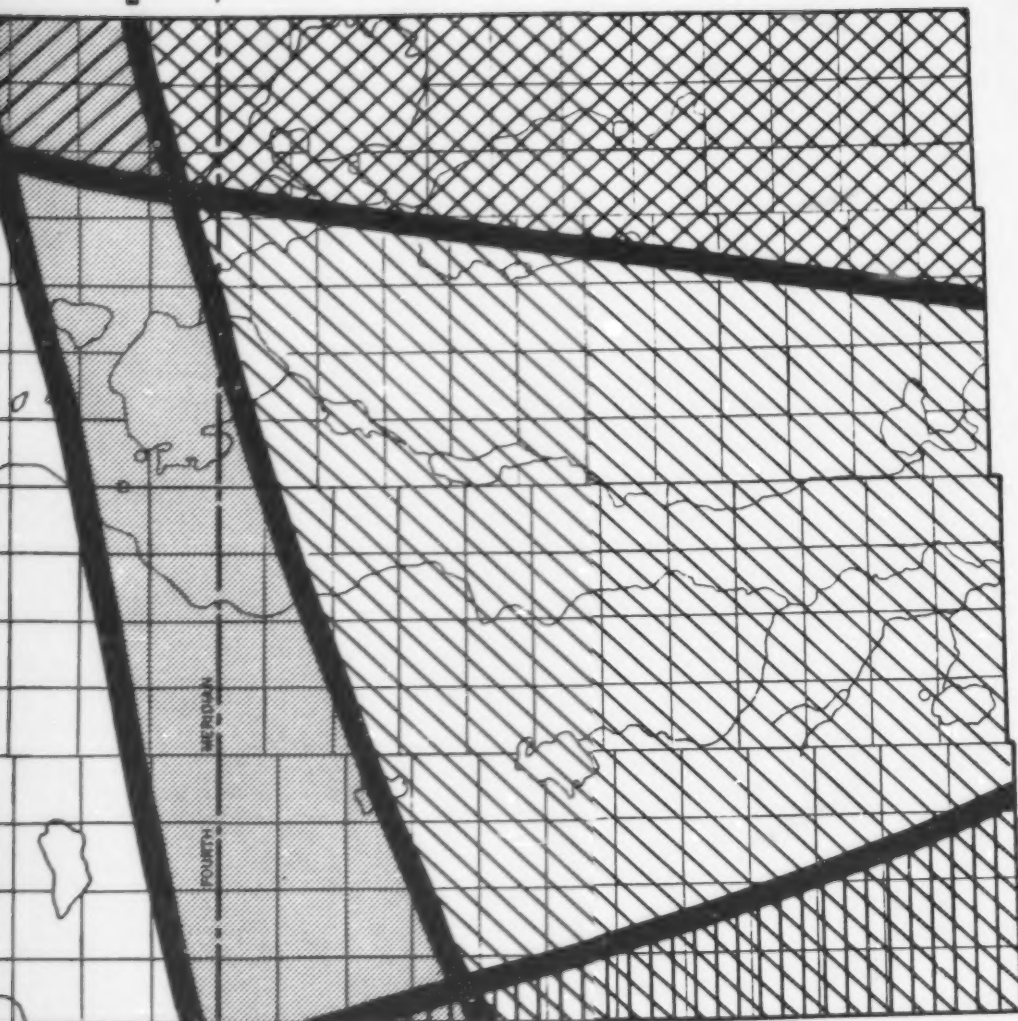
FIGURE 2-7 MAJOR INFLUENCES
FLOW IN THE CAM
(From Hamilton, 1954)

EDGE OF PRAIRIE EVAPORATE

SASKATCHEWAN

LEGEND

-  SUB CROP OF PRAIRIE EVAPORATE
-  PRAIRIE EVAPORATE ABSENT
-  CAMBRIAN / GRANITE WASH INTACT
-  CAMBRIAN / GRANITE WASH ABSENT



MEADOW LAKE ESCARPMENT

3 2 1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

50 60 70 80 90 100 km

INFLUENCES ON GROUND WATER
IN THE CAMBRIAN / GRANITE WASH
(Hamilton, 1971; Menzies, 1983a)

no data are presented north of Township 61. The Deadwood Formation of Pugh (1971) varies from 0 to in excess of 300 feet in thickness and is not present at any location north of Township 59. It is reported (Pugh, 1971) that as much as 1,000 feet of Deadwood Formation sediments were removed to the north of the Meadow Lake Escarpment during Pre-Devonian erosion. Meneley (1983b) reports a distinct change in grain size of the clastic Cambrian age sands to the north of the Meadow Lake Escarpment where a reduction in grains of sand size is noted. In addition, the Cambrian aged formations thin considerably and are absent in the northerly portion of the study area (Figure 2.7). Meneley (1983a) also reports that the Deadwood Formation is discontinuous to the north of Cold Lake.

The formation of the Meadow Lake Escarpment and the resulting impact on Cambrian age formations has a number of implications with respect to the regional hydrogeology and waste fluid injection. From a mass balance perspective, the thinning of the Cambrian will lead either to higher groundwater velocities due to a reduced cross-sectional flow area or to flow into adjacent formations. Either of these perspectives is undesirable from a waste disposal point of view. If higher groundwater velocities occur, then waste fluids introduced to the formation will flow at a higher rate towards the natural discharge area from that formation. Alternatively, flow into adjacent formations implies that some form of hydraulic connection exists to those formations. This flow may occur through low permeability confining units in which case large pressure gradients will be required to induce flow. Alternatively, flow may occur through some higher permeability media where the confining layers are absent (Prairie Formation - see Section 2.2.3). Possibilities include dissolution of either the Lotsberg or Cold Lake Formation evaporites as reported by Fuzesy (1980 in Meneley, 1983a) providing a greater amount of vertical hydraulic communication.

The discontinuous nature of the Cambrian also affects the flow and distribution of injected fluids in this formation. Predictive models generally rely on a number of assumptions such as homogeneous media of infinite horizontal extent and constant thickness. In most instances, minor deviations in these values can be tolerated without serious error. However, simulation of injection into a discontinuous zone could not be readily performed as predicted waste fluid distributions would be erroneous. Where the formation is very thin, waste fluids would migrate at a much higher rate and would travel greater distances in a given period of time. Thus, the radius of waste fluid migration could be substantially greater in areas of thin and/or discontinuous Cambrian deposits.

The data necessary to confirm these hypotheses are largely non-existent. The main source of hydrogeologic data is from oil companies who have penetrated the Cambrian in constructing disposal wells. This includes localized isopach and structure maps and formation pressures (BP, 1983; Esso, 1985a; Dome, 1985b).

2.2.1.2 Elk Point/Methy/Winnipegosis Formation. The Elk Point/Methy/Winnipegosis Formation is a carbonate sequence of Middle Devonian age directly underlying the Prairie Formation (Figure 2.1, 2.4). The main point that arises with regard to this formation is whether or not extensive dissolution and/or karst features exist within the study area and if so what is the impact on waste fluid migration. Existing studies (ARC, 1985g; Meneley, 1983a) report the existence of reefal structures within this formation which may be up to 200 m in thickness; however, the location of these reefal structures and whether or not they are in the study area are not reported. The implications of extensive dissolution features are that the vertical and/or horizontal permeability could be substantially greater such that groundwater velocities (Darcy) would be higher for a given hydraulic gradient. Coincident increases in porosity are not likely to be of

the same order of magnitude of those observed for permeability such that the porosity increase will not affect velocity to the same degree. Groundwater flow will occur preferentially in the dissolution features and will travel at a much greater velocity. Waste fluids entering this formation will be advected at potentially much higher rates vertically and/or horizontally.

2.2.1.3 Prairie Evaporite. The Prairie Evaporite or Prairie Formation of Middle Devonian age is a thick sequence of evaporites (primarily salts) which have been considered as a barrier to groundwater flow (i.e., an aquitard) in previous investigations (Meneley, 1983a; ARC, 1985c). ARC (1985i) considered the formation to be of sufficiently low permeability to act as the lower boundary of a groundwater flow model of the Upper Devonian and Cretaceous Formations. Meneley (1983a) postulated that this formation likely isolates the Upper Devonian Cooking Lake - Beaverhill Lake - Watt Mountain Aquifer from the Elk Point/Methy/Winnipegosis formation which is also believed to behave as an aquifer (Meneley, 1983a). However, these hypotheses have not been confirmed to date and there exists uncertainty (aquifer versus aquitard) in the hydraulic properties of this formation.

The main point of significance to waste fluid injection is that the edge of the Prairie Evaporites has been undergoing dissolution and that this zone of dissolution passes through approximately the center of the study area (Figure 2.7). The absence of this formation allows hydraulic connection between the Middle Devonian and older formations (i.e., Cambrian) and the formations overlying the Prairie which are the Cretaceous Mannville Group and Middle Devonian CBWA in the vicinity of the solution edge. Thus, in the area of the northeast limit of the solution edge, groundwater may readily flow between the Cambrian, Middle Devonian and Cretaceous age formations.

The hydrogeology is further complicated by collapse features present within the vicinity of the solution edge as far west as the edge of undissolved salt (Figure 2.7). These collapse features

reportly extend into the overlying strata as is evident in structure contours for these younger formations (ARC, 1985g). The ARC (1985g) studies noted broad synclinal structures in structure contours of formations in the area overlying the area of dissolution for formations as young as Upper Cretaceous age (i.e., Second White Speckled shale). It is highly likely that these areas of collapse have a significantly higher vertical permeability than the intact rock. Thus, the area overlying dissolution could potentially provide a pathway for fluid migration from the Middle Devonian and possibly the Cambrian to the Upper Cretaceous.

2.2.1.4 Ireton Formation. The shales of the Ireton Formation are considered by most investigations (ARC, 1958i; ARC, 1985g) to act as an aquitard separating the flow of groundwater in the CBWA from that in the overlying Cretaceous Mannville Group. The shale is present throughout the west and southwest portions of the study area as shown in Figure 2.8. The shale is penetrated locally by reefal structures of the Leduc Formation and the effective thickness of the shale is less where a facies change occurs and carbonates of the Grosmont Formation replace the upper shale (ARC, 1985g).

In the area where the Ireton is absent, the CBWA is in direct hydraulic communication with the Lower Mannville Group as is evidenced in the similarity in hydraulic heads (pressures) in the two formations (ARC, 1985i). Thus, groundwater and/or waste fluids in the CBWA in the vicinity of the edge of the Ireton (Figure 2.8) or in fact near to the subcrop of the Ireton may readily flow into the Lower Mannville Group. This is illustrated in Figure 2.4. The ability for waste fluid containment in the CBWA is highly questionable in this area.

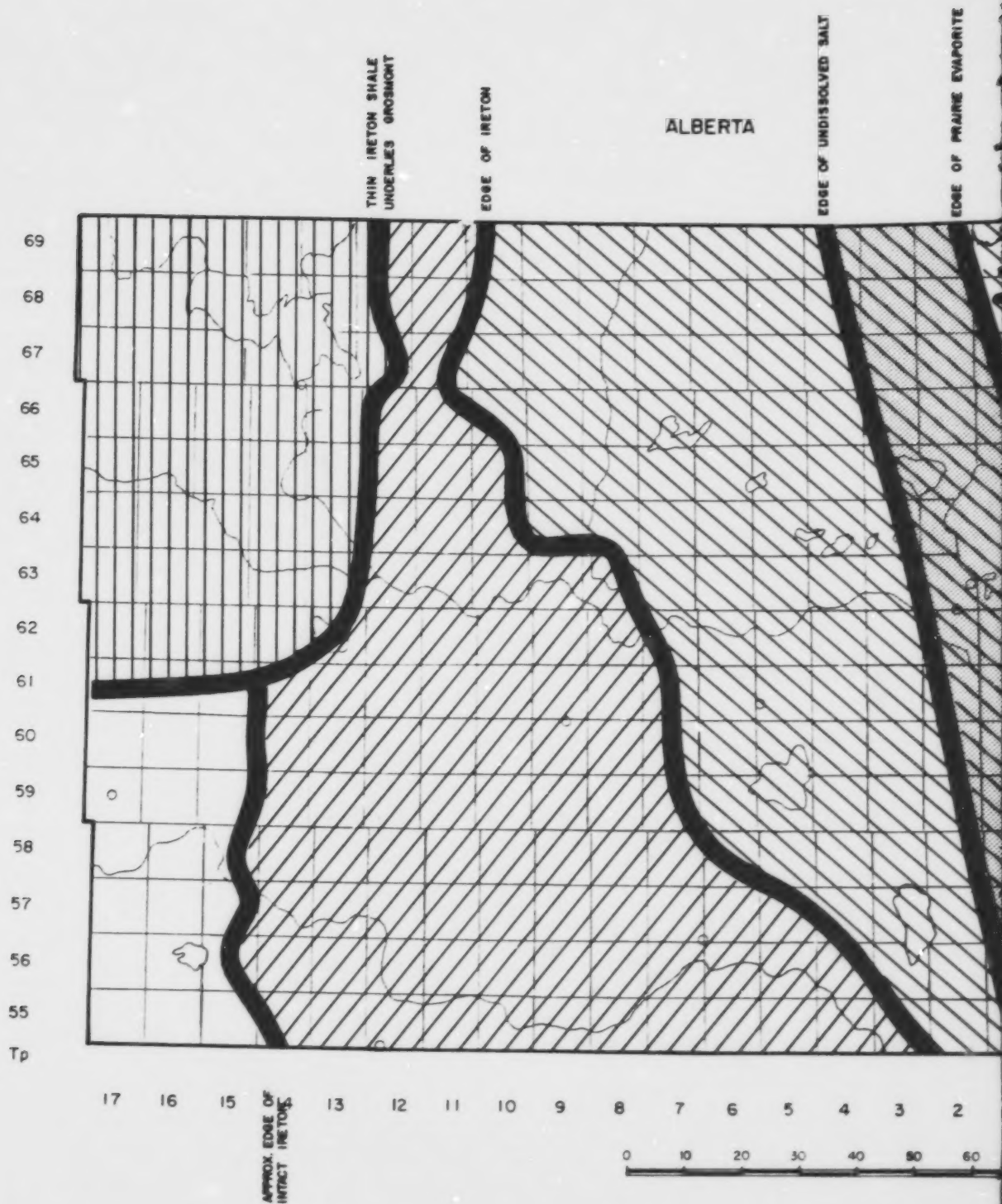


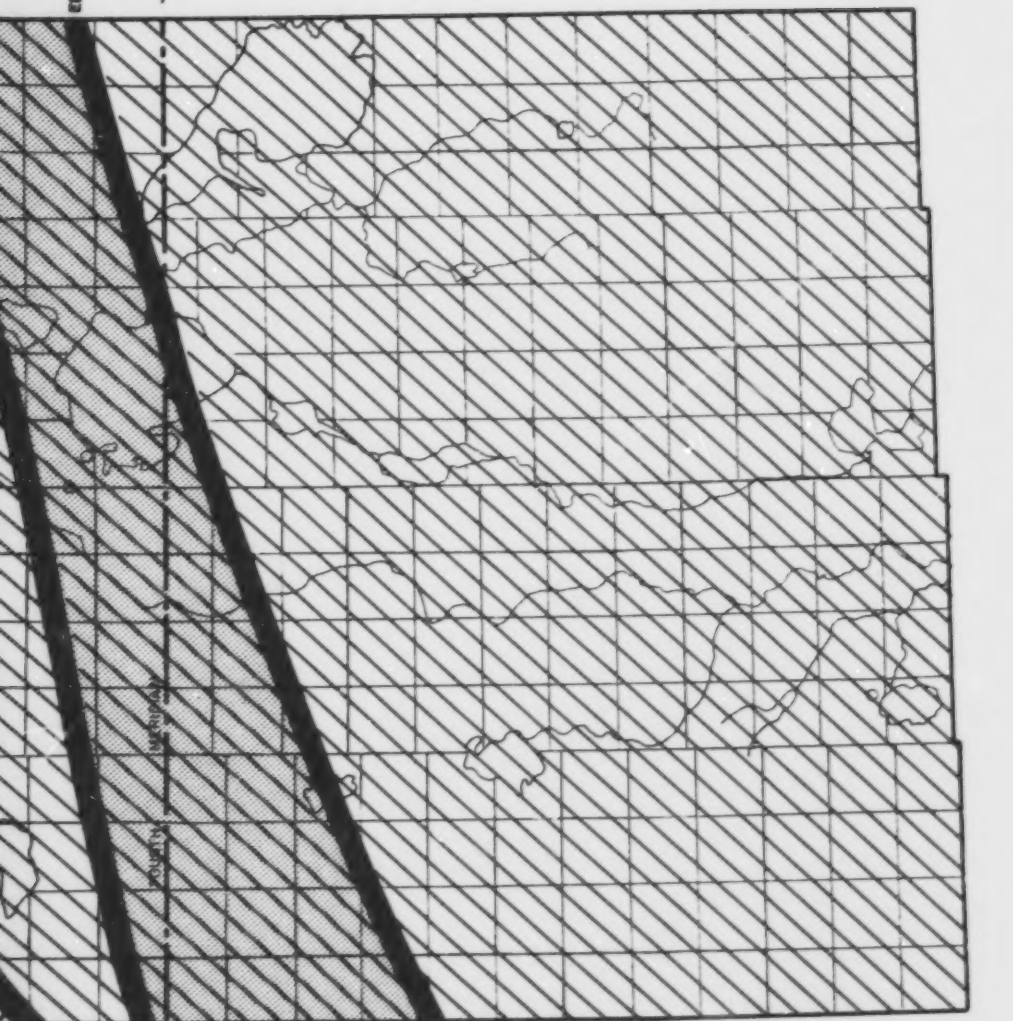
FIGURE 2-8

MAJOR INFLUENCES
FLOW IN THE CBW

SASKATCHEWAN

LEGEND

-  PRESUMED AREA OF COLLAPSE FEATURES DUE TO DISSOLUTION OF THE PRAIRIE EVAPORITE
-  SUB CROP AREA OF CBWA
-  SUB CROP AREA OF IRETON SHALE
-  IRETON SHALE THINS AND IS STRATIGRAPHICALLY REPLACED BY THE GROS MONT FORMATION
-  IRETON SHALE INTACT



2 1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

0 60 70 80 90 100 km

INFLUENCES ON GROUND WATER
THE CBWA (From ARC, 1985g; Hamilton, 1971)

2.2.1.5 Pre-Cretaceous Unconformity. The pre-Cretaceous Unconformity (PCU) is the zone at which the Cretaceous deposits unconformably overly the Devonian and/or older formations (Figure 2.2). Erosion in late Paleozoic time has reportedly lead to an enhanced permeability in this zone. Formations of significantly different age are in direct hydraulic connection across the PCU. In fact, pathways may exist by which formation fluids originating in pre-Cretaceous formations may flow into a seemingly isolated pre-Cretaceous formation via flow through or along the PCU and the Lower Mannville.

2.2.1.6 Clearwater Formation. The argillaceous Clearwater Formation separates the Upper and Lower Mannville Group throughout most of the study area except in the south-southeast (Figure 2.9). The Clearwater Formation is considered as a aquitard by ARC (1985c) which isolates groundwater flow between the Upper and Lower Mannville. Where this formation is absent, these two formations are connected to each other and possibly to deeper formations where both the Ireton and/or Prairie Evaporite is absent (see Figure 2.9, 2.4). However, the ability of the Clearwater to act as an aquitard is somewhat questionable. The formation is generally 10 metres or less in thickness which is much less than the other aquitards identified in the regional groundwater flow system (i.e., Prairie). It should also be noted that the hydraulic characteristics of the Clearwater are largely undocumented. Six disposal wells are reported (ERCB, 1986, Appendix A) to be completed in the Clearwater suggesting that the formation has a significant permeability but it is possible that the disposal interval is connected to the Upper or Lower Manville. In addition, ARC (1985i) noted a vertical gradient of one across the Clearwater, the lowest gradient observed for any of the confining units identified. This suggests that the vertical permeability of the Clearwater is higher than the other confining units (i.e., Colorado Shales, Joli Fou Formation). As a result, it is difficult to assess the affect of the Clearwater on regional groundwater flow. Based primarily on the designation by ARC, in this study, the Clearwater Formation is assumed to provide some degree of isolation between the Upper and Lower Mannville.

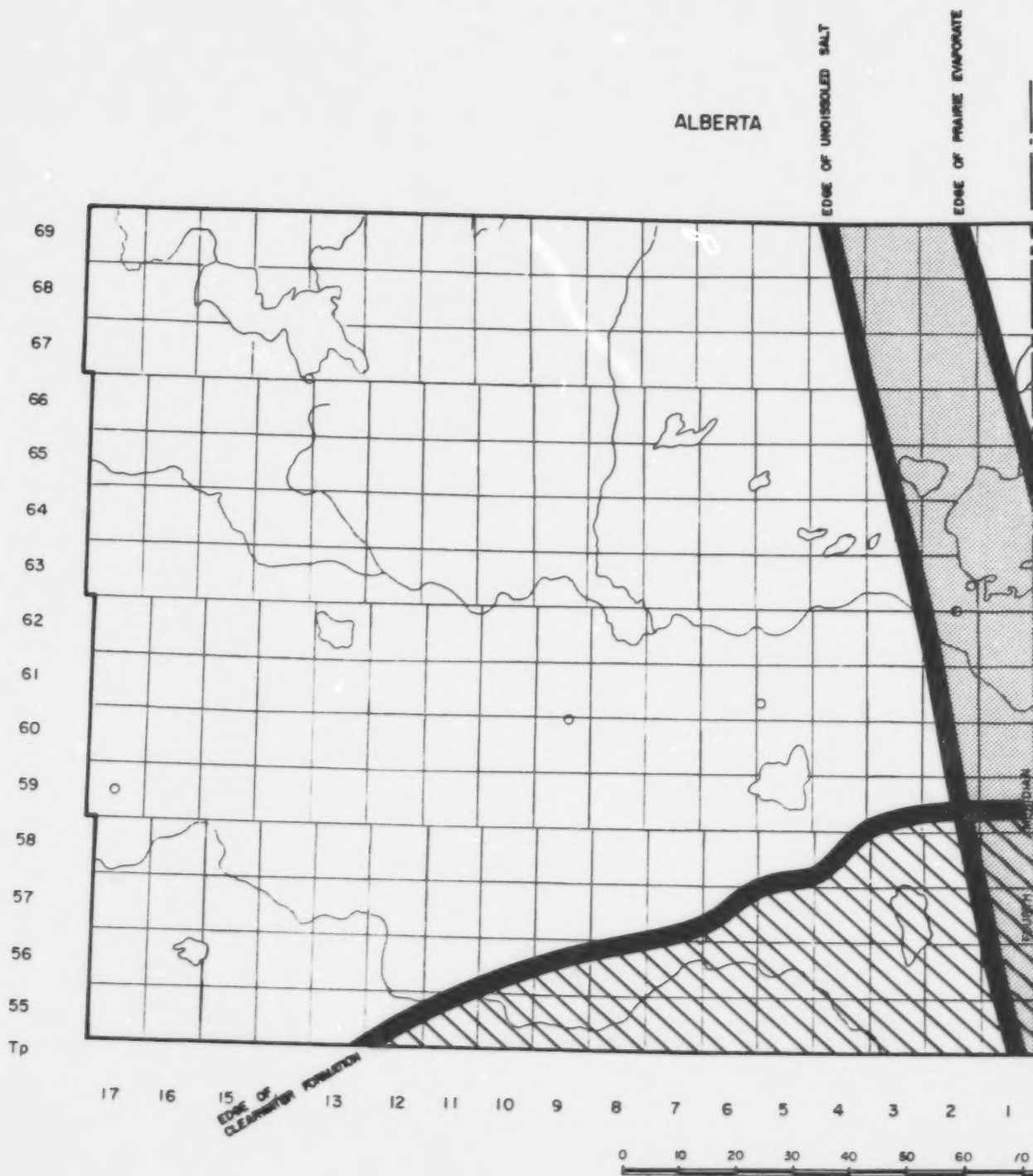


FIGURE 2-9 MAJOR INFLUENCES ON
FLOW IN THE MANNVILLE
(From ARC, 1985g ; H)

SASKATCHEWAN

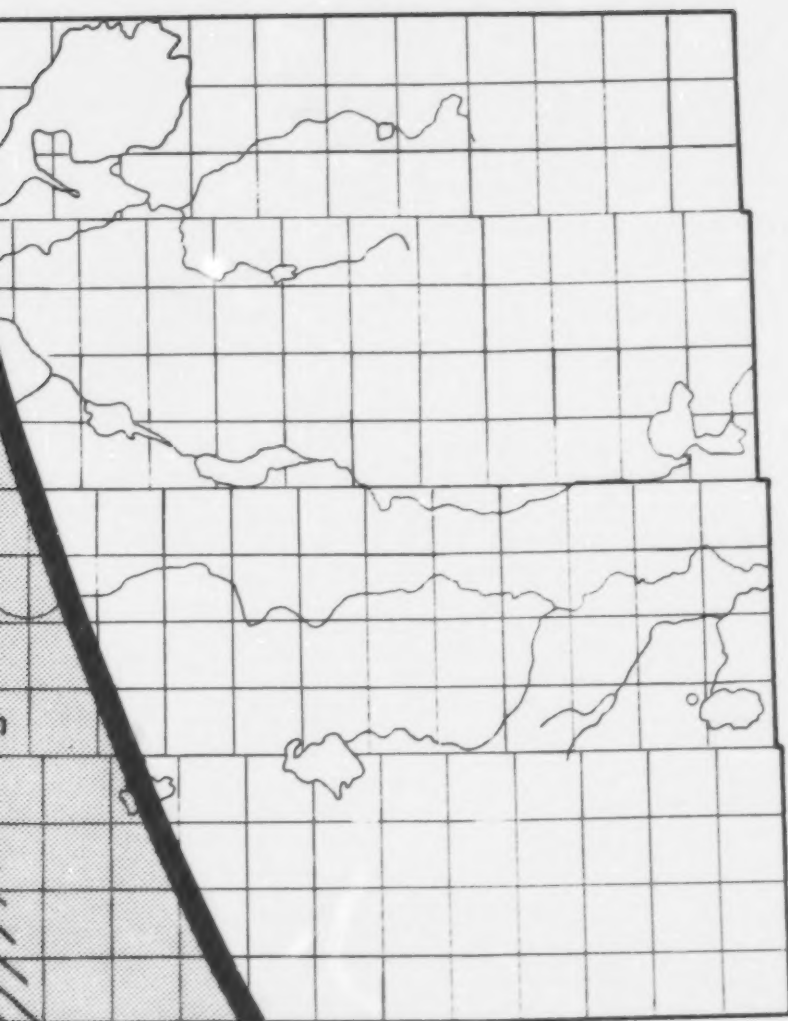
LEGEND



PRESUMED AREA OF
COLLAPSE FEATURES DUE
TO DISSOLUTION OF THE
PRAIRIE EVAPORATE



CLEARWATER FORMATION
ABSENT



27 26 25 24 23 22 21 20 19 18 17 16 Rg

80 90 100 km

GROUND WATER
E GROUP
(Milton, 1971)

2.2.1.7 Mannville Group. A number of the members of the Mannville Group are currently used for waste fluid injection. In addition, the Mannville Group is hydraulically connected to older formations (i.e., CBWA, Cambrian/Granite Wash) at a number of locations. Waste fluids injected into these older formations may migrate to the Mannville via a number of different routes discussed in other sections of this chapter. As a consequence, the question is raised as to the hydraulic connection of the Mannville Group to shallower groundwater flow systems and the surface water system.

ARC (1985g) observed that the Colorado Group overlying the Mannville Group is present throughout the entire Alberta portion of the study area (Figure 2.2) although it thins to the northeast in Saskatchewan (Figure 2.4) (McCrossan and Glaister, 1966). This group likely acts, for the most part, as a aquitard with the exception of the Viking Sandstone comprising one of the members.

Vertical hydraulic gradients are directed downward within the Upper Mannville Group Aquifer (above the Clearwater) and in the Viking Sandstone. Thus, it is likely that vertical groundwater flow upward through the Colorado Group is limited to very localized areas and to areas where an alternative pathway exists (i.e., collapse zones, abandoned wells, faults). On the other hand, Meneley (1983a) identified a number of lows in the equivalent fresh water heads of the Mannville Group which coincide with some of the bedrock valleys of the area. A major groundwater low in the Mannville was observed in the vicinity of the Hatfield Valley from Cold Lake west to the Athabasca River and east to the Beaver River (Figure 2.10). Similar observations were made by ARC (1985i) in comparing heads between the Cretaceous Belly River Group and the Quaternary Empress Formation where the potential for upward vertical flow was noted. Within the Empress Formation, good hydraulic connection exists to the major surface water bodies overlying the main buried valleys throughout the Alberta portion

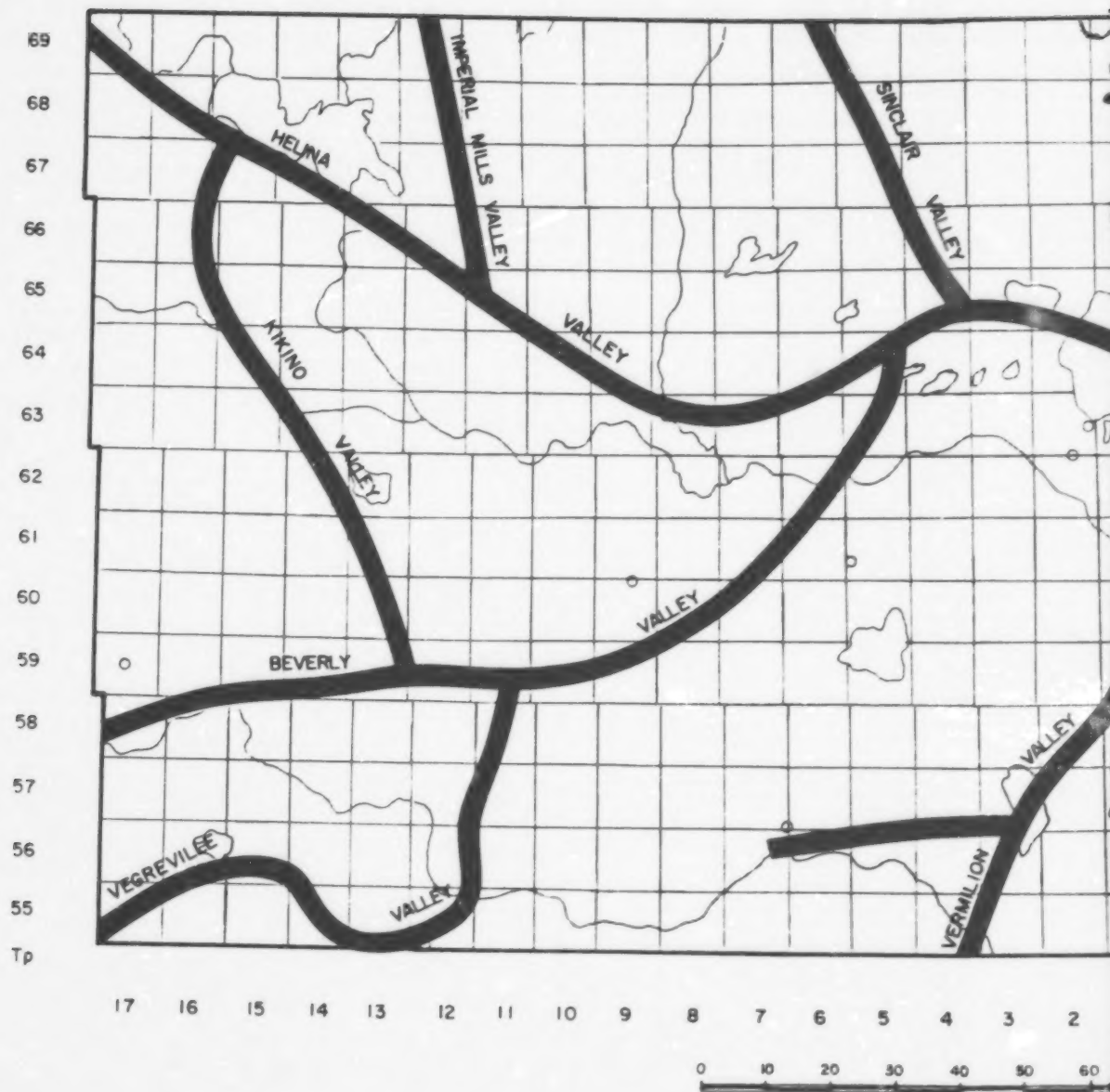
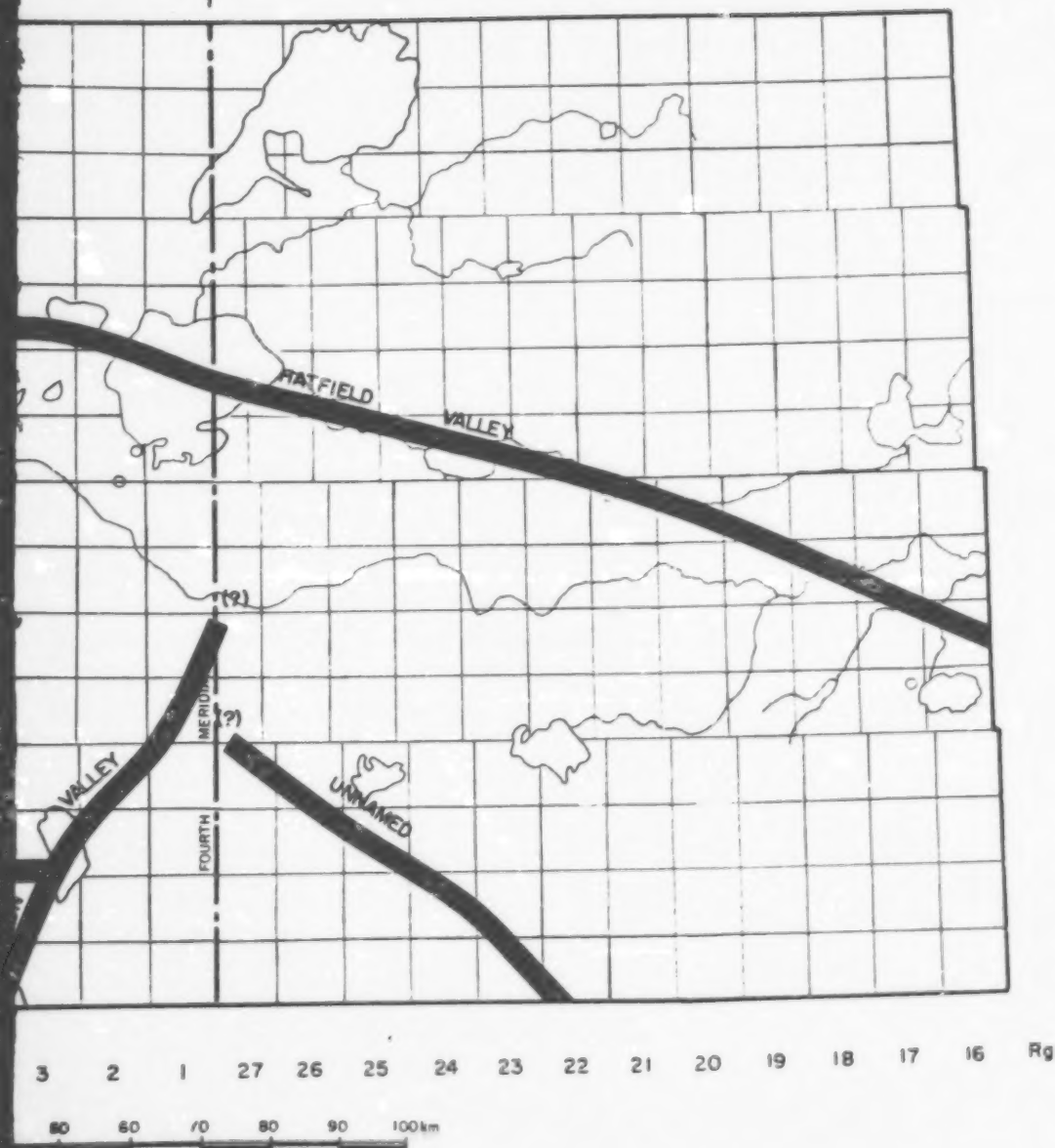


FIGURE 2-10 APPROXIMATE AL
(From Yoon and
Gold et al, 1983 ;
Meneley, 1983a ; C

SASKATCHEWAN

APPROXIMATE
ALIGNMENT OF
BURIED VALLEY



APPROXIMATE ALIGNMENT OF MAJOR BURIED VALLEYS

Yoon and Pluym, 1974; Whitaker and Christiansen, 1972;
 et al, 1983; Whitaker and Pearson, 1972; ARC, 1985g;
 et al, 1983a; Carlson, 1972; Carlson and Currie, 1973)

of the study area (Figure 2.4). These areas of lower heads suggest that vertical groundwater flow may be occurring from the Mannville to overlying units in some localized areas.

Alternatively, Meneley (1983a) suggests that these anomalous areas may be attributed to the relict flow systems first discussed by Toth. That is, the heads in the present day groundwater flow system have not equilibrated following the most recent period of glaciation. The anomalous head values are due to the transient state of the groundwater flow system which is tending towards equilibrium with the present day hydrogeologic controls.

Although no attempts have been made to assess specifically the potential for groundwater flow from the Mannville Group to the Quaternary, there is some evidence to suggest that this phenomena exists in localized areas. Given that waste fluids are injected under pressures above formation pressures, a greater hydraulic gradient will be created which may lead to greater fluid movement into the Quaternary. This hypothesis is presently unconfirmed.

2.2.1.8 Hydrofracturing. Hydrofracturing is a technique commonly used in the oil industry to stimulate the production of oil and/or gas from a reservoir as well as to enhance the ability of a formation to accept waste fluids. Hydrofracturing involves injecting a fluid at pressures sufficient to induce fracturing. The induced fractures are typically propped open using a granular material (i.e., sand), termed a propping agent, which is suspended in the injection fluid. The success of hydrofracturing is governed by a number of factors including the rock properties (i.e., porosity, permeability, composition, strength, in situ stress), the type of reservoir fluids (i.e., oils, gases, mixtures) and the reservoir properties (i.e., pressure, depth, temperature). However, the large number of variables involved and the relative uncertainty in quantifying their values makes accurate prediction of fracture propagation difficult. This has a number of implications with regard to the movement of waste fluids.

For instance, if a fracture was to propagate at an angle other than horizontal, it will at some point reach the stratigraphic layer confining fluid in the injection formation. If the fracture is propagated into the confining layer, a pathway for waste fluid escape to overlying units will exist. Alternatively, the fracture may propagate along the boundary of the two formations leading to higher migration rates in the vicinity.

The theory governing fracturing predicts that a fracture will form perpendicular to the least principal stress (Root, 1978). It is reported, from both research studies and field observations, that the majority of fractures form in the vertical direction as the least principal stresses are oriented horizontally (Root, 1978).

A further concern related to hydrofracturing is that vertical fracture propagation may provide a connection to one or more of the evaporite formations present in the study area. Circulation of injected fluids past the evaporites may lead to dissolution and possible breach.

Given the uncertainties involved in hydrofracturing and the potential implications on waste fluid migration, areas where hydrofracturing has been performed are of concern in addressing the impact of waste fluid injection. This includes hydrofracturing in relation to both waste fluid injection and heavy oil extraction. ARC is presently studying the effects of hydrofracturing as potential avenues of waste fluid release.

2.2.1.9 Abandoned Oil and Gas Wells. The abandonment procedures for oil and gas wells are discussed in Section 2.1.5. The current and past regulations for well abandonment have a number of implications with regards to waste fluid injection. For instance, the basic requirements (may be modified as required) for abandoning cased holes are that a bridge plug topped with several metres of cement be installed just

above the casing perforations. This procedure is quite adequate so long as the casing remains intact. However, most wells pass through corrosive brines which attack and eventually corrode the well casing. Failure of the well casing may not occur for 50 to 100 years or longer but at this time a pathway for waste fluid migration will exist throughout the depth of the well. Waste fluids at higher pressures may then migrate up through the abandoned casing and potentially into overlying potable groundwater supplies provided a pathway out of the casing exists. Casing failures due to heat stress in steamed zones have also occurred in the past. The requirement for thermal cement through steamed zones has only been in place for approximately one and one half years so that any wells installed prior to this time may be subject to this problem (Davis, 1986). Thus, fluids injected below a steamed zone may migrate into the steamed zone through a casing failure.

2.2.1.10 Casing/Completion Failures. A possible route for waste fluid migration away from the target injection horizon is via failures or inadequacies in the well completion. These problems are most critical for the injection wells but this discussion applies equally to any other wells penetrating the injection horizon. Possible problems include:

- inadequate bond between cement and casing;
- incomplete wellbore to casing seal (i.e., voids);
- cracking or fracturing of cement (i.e., due to vibration, poor cement mix, thermal expansion/contraction);
- waste fluid/cement interactions;
- corrosion of casing;
- thermal stress failure of casing.

One or a combination of these problems may lead to possible upward leakage of waste fluids.

3.0 FIELD PROGRAM DESIGN

3.1 EVALUATION OF HYDROSTRATIGRAPHIC UNITS FOR WASTE INJECTION POTENTIAL

The purpose of the hydrostratigraphic unit evaluation is to provide an objective assessment of the potential waste injection horizons and to determine which formation is most desirable for accepting waste fluids as a function of location. Three potential injection horizons, namely, the Mannville Group, the Cooking Lake - Beaverhill Lake - Watt Mountain Group and the Cambrian/Granite Wash, were evaluated both independently and jointly to determine which is most suitable for waste fluid injection. (Note: Other injection horizons such as the Winterburn and Woodbend Groups were excluded from this study by the terms of reference for the project.) A constraint mapping process was used in this evaluation to assess the areal variations in suitability.

Constraint mapping involves developing a number of criteria which are assigned a numerical weighting based on their relative importance. Rankings are assigned for each of the criteria selected and the rankings are summed with the higher number, in this case, indicating a more preferred area relative to the lower numbers. Although constraint mapping does involve a certain amount of subjectivity in selecting weighting factors for the criteria, it can provide a reasonably objective guide when a prudent selection of weighting factors occurs. In this study, an attempt was made to select criteria which were unbiased yet adequately characterized the subsurface conditions. Also, weightings were assigned based on an understanding of processes governing waste fluid injection and the subsequent impacts. As a result, the process is considered to provide a reasonably good guide for selecting injection horizons.

In this study, the study area was evaluated using constraint mapping applied on a township by township basis (10 km x 10 km). Rankings were assigned for each township based on the most applicable ranking for 50% or greater of the township area. The constraint

mapping was performed for each of the three potential injection formations. The Elk Point/Methy/Winnipegosis Formation was not considered due to the large paucity of information characterizing this formation. The results of constraint mapping within each formation were compared to assess which formation was either the most suitable, questionable or least suitable for waste injection. Rankings for each township were determined, with the townships scoring higher being the ones most suitable for waste injection.

The criteria used in constraint mapping were developed based on a number of different sources of information which characterize the suitability of a formation for waste fluid injection. These include geologic, hydrogeologic and resource related information.

The specific criteria which were developed are listed in Table 3.1 along with the designations and weightings. These criteria are considered to encompass the relevant concerns in assessing a potential injection horizon. In some cases the criteria may overlap to some extent which could be considered as double counting, however, the significance of each criterion in the evaluation is considered justification for the overlap. Further criteria were initially considered but consistent information was not available throughout the entire study area preventing use of these additional criteria. Most notably, geochemical information in the form of formation/waste fluid compatibility was initially considered but was later found to be too limited to facilitate consistent application over the entire study area.

The evaluation and ranking of each potential injection formation is discussed in Appendix B. Within this Appendix, the ranking assigned for each criterion and the rationale for that ranking are discussed.

Table 3.1 Criteria for Hydrostratigraphic Unit Evaluation

Hydrostratigraphic Unit Assessment Criteria		Designation and Weighting	
A. <u>Geologic Information:</u>			
A1.	Frequency of Structural Discontinuities (i.e., faults, fracture zones)	High (1)	Intermediate (3)
A2.	Proximity to Major Structural Influences on Groundwater Flow (i.e., pre-Cretaceous Unconformity, Pinch-Out of Prairie Formation or Ireton Formation)	0 - 5 km (1)	Low (5) 5 - 20 km (5) > 20 km (10)
B. <u>Hydrogeologic Information:</u>			
B1.	Proximity to Groundwater Discharge Zone	0 - 5 km (1)	> 20 km (5)
B2.	Formation Transmissivity: $(T = Kb = \frac{\rho g}{\mu} kb)$	$< 10^{-4} \frac{m^2}{s}$ (1)	$10^{-4} - 10^{-2} \frac{m^2}{s}$ (5) $> 10^{-2} \frac{m^2}{s}$ (10)
B3.	Formation Permeability	$< 10^{-13} \frac{m^2}{s}$ (1)	$> 10^{-11} \frac{m^2}{s}$ (5)
B4.	Matrix Porosity	< 0.15 (1)	0.15 - 0.30 (5)
B5.	Injection Zone Continuity/Areal Extent (horizontal direction)	Discontinuous (1)	Limited Continuity (5)
B6.	Containment Capabilities/Integrity of Confining Units	Low (1)	Intermediate (5)
B7.	Primary Groundwater Flow System	Local (1)	Intermediate (3)
B8.	Breach Potential due to Abandoned or Active Oil and Gas Wells	High (1)	Intermediate (5)
B9.	Potential for Hydraulic Communication with Potable Water Supplies	High (1)	Low (20)
B10.	Injection Formation Depth Below Surface	Shallow (1)	Intermediate (10) Intermediate (5) Deep (10)
C. <u>Resource Information:</u>			
C1.	Future Resource Potential of Formation	High (1)	Intermediate (3)
C2.	Potential Interference with Existing Resource Extraction Sectors	High (1)	Low (5) Low (5)

The individual rankings assigned to each township are documented in Tables B-1 through B-3 in Appendix B. The criteria utilized are as follows:

A. Geologic Information:

A1. Frequency of Structural Discontinuities

The criterion regarding frequency of structural discontinuities was intended to account for structural features such as faults, fracture zones and predominant trends in fracture orientation. These features affect the containment capabilities of an injection zone as well as the behavior of fluid migration and the pressure build-up.

A2. Proximity to Major Structural Influences on Groundwater Flow

This criterion was derived from considerations of regional groundwater flow patterns and a knowledge of the potential effects of major structural features on groundwater flow. Major structural features considered are those which may facilitate hydraulic communication between two or more zones which are otherwise isolated. Many of these features are discussed in Section 2.2.1 of which the most notable are the pinch-out of the Prairie Formation, the collapse zone overlying the subcrop of the Prairie Formation, the Meadow Lake Escarpment and the pinch-out or subcrop of the Ireton, CBWA, Cambrian/Granite Wash and the Clearwater Formations. The candidate areas were ranked as to the distance away from these major structural features with the greater distance receiving a higher ranking.

B. Hydrogeologic Information:

B1. Proximity to Groundwater Discharge Zone

In the hydrostratigraphic unit evaluation, groundwater discharge zones are considered as areas where formation waters flow out of or are discharged from a formation. Discharge zones occur in areas where a formation subcrops as well as in areas where predominantly vertical groundwater flow is occurring between formations. Groundwater discharge zones are important in that they represent a point of waste fluid release from the injection formation. Although this release may occur at depth, it represents an additional uncertainty in the formation's ability to contain the waste fluids.

The criteria selected considers the distance of the candidate township from the estimated groundwater discharge area. Distance ranges of 0 - 5 km, 5 - 20 km and greater than 20 km were considered reasonable in characterizing the candidate township with the greater distance assigned a higher ranking.

B2. Formation Transmissivity

Formation transmissivity (T) is characteristic of the amount of fluid that a formation can produce or alternatively accept. It is defined as the volume of fluid which a formation will yield per unit width per unit time and can be calculated with a knowledge of formation hydraulic conductivity (K) and thickness (b), as follows:

$$T = Kb = \frac{\rho g}{\mu} kb$$

k = permeability;

ρ = fluid density;

g = gravitational constant;

μ = fluid viscosity.

Typical values for hydraulic conductivity or permeability were selected for each formation from reported values (Tables 2.1 to 2.6) and the transmissivity was calculated based on formation thickness from available isopachs.

The ranges of transmissivities used as criteria were based on the desirable hydraulic characteristics of an injection zone. That is, values which allow fluids to be injected at reasonable flow rates without large build-ups in injection pressures.

B3. Formation Permeability

The formation permeability (k) is related to the velocity at which fluids can move into and through the pore spaces of geologic media through the equation.

$$v = \frac{ki}{\theta}$$

v = interstitial velocity;

k = permeability;

i = hydraulic gradient;

θ = porosity.

Thus, at higher permeabilities, the injected fluids flow more readily into the formation and larger flow rates can be accommodated without large pressure build-ups.

The criteria selected for permeability characterize the ranges of greatest to least desirability for fluid injection. However, in reviewing reported values of formation permeability, it was observed that typical values for each formation varied very little between the three formations present and that the range of values for any particular formation varied over approximately four orders of magnitude (Tables 2.1 to 2.6). As a consequence, consideration of formation permeability did not provide great insight into selecting the most appropriate injection formation but was included due to its relevance to waste fluid injectability.

B4. Matrix Porosity

The matrix porosity is characteristic of the volume of fluids which can be contained within a volume of geologic media. The matrix porosity is defined as the ratio of the volume of the voids to the total volume. In addition, the porosity is theoretically inversely proportional to the radius of migration of waste fluids from an injection well. That is, at higher porosities, the radius of waste fluid migration will be less than at lower porosities for a given volume of fluid. Matrix porosities (defined and discussed in Section 3.3.1) are typically measured by the oil industry by testing of drill cores. As a result, porosity values were readily available for consideration in the constraint mapping program.

The ranges of matrix porosity values selected in the assessment criteria (Tables 2.1 to 2.6) were derived based on the range of values observed for the study area as well as the values desirable for waste fluid injection.

B5. Injection Zone Continuity/Areal Extent

The continuity and areal extent of a potential injection zone has a direct bearing on its ability to contain waste fluids. In areas where the injection zone is discontinuous or of limited continuity, waste fluids are likely to flow into adjacent formations. Alternatively, fluids may flow at higher rates due to the reduced thickness or flow area of the formation. For this reason the injection zone continuity is considered in the constraint mapping.

In evaluating injection formation continuity, the formation was generally considered to be intact in areas remote from the subcrop areas and edge of the formation. In the subcrop areas, the formation was considered to be of limited continuity and in the vicinity of the edge of a formation (pinch-out), the formation was considered to be discontinuous.

B6. Containment Capabilities/Integrity of Confining Units

The containment capabilities of an injection zone area are also a function of the integrity of the overlying confining units. Confining units are considered to be lower permeability formations which act to hydraulically isolate the injection formation from other formations both above and below. Thus, the integrity of these confining formations has a direct bearing on the ability to contain fluids within the injection zone.

Typically, the integrity of the confining units were considered as high in areas remote from their subcrop zone, intermediate in the subcrop zone and low where the confining layers were absent. Additional factors accounted for may include structural features which affect the condition of the confining units (i.e., collapse zone over Prairie Formation subcrop zone).

B7. Primary Groundwater Flow System

Regional groundwater flow systems are often broken down into local, intermediate and deep components which are instructive in assessing potential affects of waste fluid injection. Local groundwater flow is that which is governed by local topography for which small creeks and lakes act as boundaries to groundwater flow. Deep flow systems are typically controlled by major physiographic features such as mountain ranges. In the study area, the deep groundwater flow system is considered to extend from recharge areas at the foothills of the Rocky Mountains to discharge along the Canadian Shield in Saskatchewan, Manitoba and the Northwest Territories. Deep groundwater flow is not affected by local surface features and most surface water bodies. Intermediate flow systems fall between local and deep flow systems and are controlled by larger rivers and lakes. Although the boundaries between these flow systems are not well defined, the classification is useful in assessing the potential impacts of waste injection.

B8. Breach Potential Due to Abandoned or Active Oil and Gas Wells

In areas where active or abandoned oil or gas wells penetrate the injection horizon, a potential exists for migration either along or through the casing. This may occur due to casing failures, poor completions or inadequate abandonment as discussed in Section 2.2.1. Thus, areas where wells currently exist or existed in the past have a lower desirability as waste injection horizons.

The breach potential for a particular formation due to migration of waste fluids through abandoned or active oil and gas wells was established by assuming that the breach potential is high in areas of known hydrocarbon reserves where wells likely exist. Thus, formations with known reserves as well as formations which are in hydraulic connection to these formations are considered to have a high potential for waste fluid release through oil or gas wells. The location of oil and gas reserves is documented in ARC (1985a) and shown in Figure 3.1. These reserves are limited to the Cretaceous Mannville Group.

B9. Potential for Hydraulic Communication with Potable Water Supplies

The impact of waste disposal operations on potable groundwater supplies is a key concern. Although a formation may be desirable based on its hydraulic properties, it is not acceptable if a potential exists to release waste fluids into potable groundwater zones. For this reason, the potential communication of the injection zone with overlying potable water is adopted as a criterion and is weighted somewhat higher than other criteria due to its perceived significance.

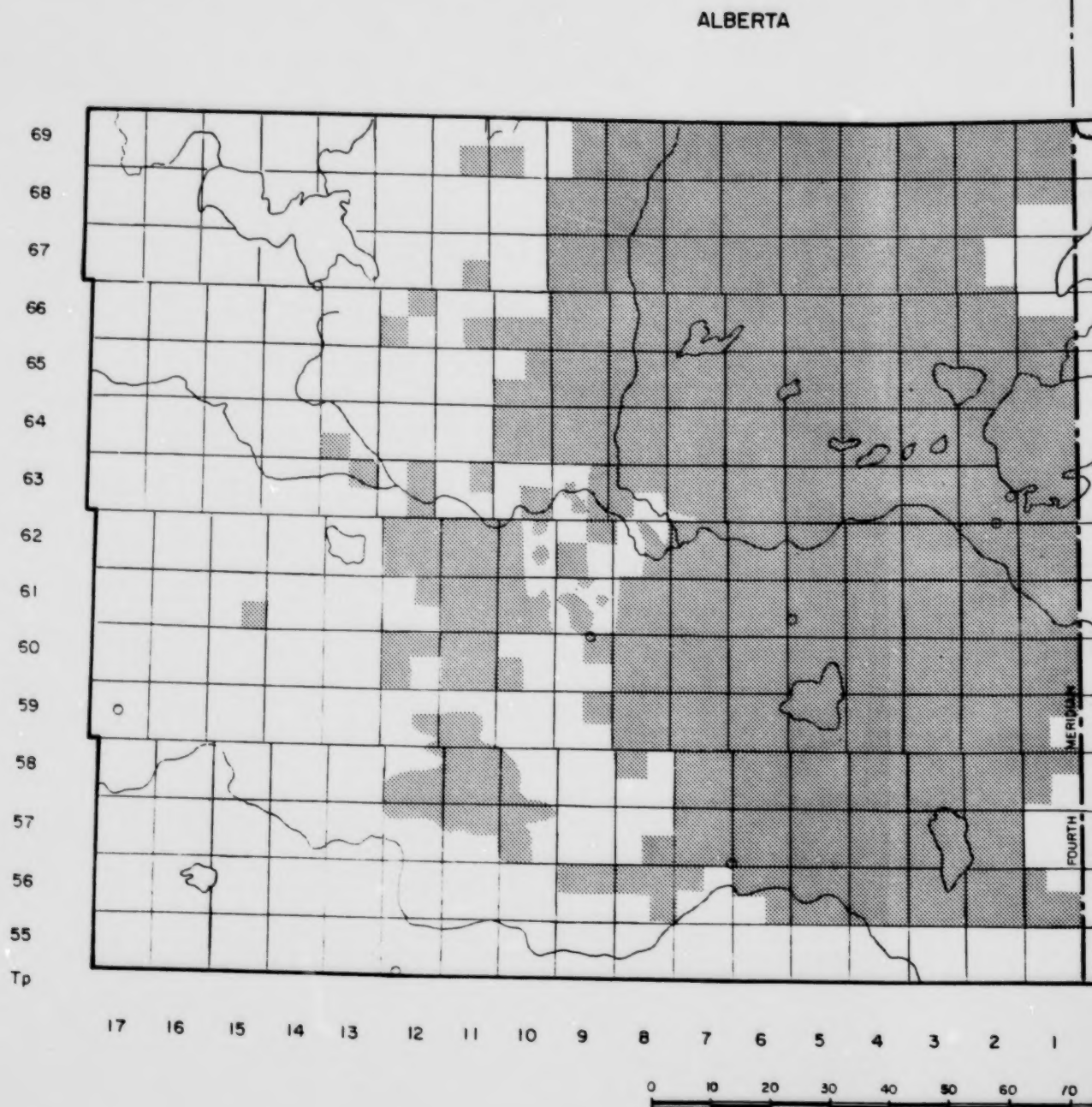


FIGURE 3-1

OIL & GAS RESERVES
(After ARC, 1985a)

SASKATCHEWAN

 OIL AND/OR GAS POOLS
IN CRETACEOUS AND
DEVONIAN STRATA



1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

0 70 80 90 100 km

RIVES IN THE CRETACEOUS
 5)

B.10 Injection Formation Depth Below Surface

The depth of an injection formation has a direct bearing on the potential for waste fluid release to the near surface environment. The relative depth of the injection formations has consequently been used in the constraint mapping.

C. Resource Information:

C1. Future Resource Potential of Formation

Injection of waste fluids into a formation which may be exploited in the future due to its resource potential is considered unadvisable. Waste fluids may migrate to the vicinity of the resource (i.e., hydrocarbons) and subsequently be extracted. The waste fluids must then be handled jointly with the resource possibly complicating the extraction process. Also, the waste fluids must be redispersed through an acceptable method. Consequently, formations with potentially usable resources are ranked low in the constraint mapping process.

C2. Potential Interference with Existing Resource Extraction Sectors

The potential for waste fluid injection to interfere with existing resource extraction operations (specifically heavy oil extraction) is also a concern. As mentioned previously, waste fluids may be pumped back to surface with the heavy oil at which point they must be handled and disposed in an environmentally satisfactory manner. To avoid the potential for waste fluids to return to surface, it is advisable that injection wells not be located near existing heavy oil or gas extraction operations.

3.1.1 Results of Evaluation of Hydrostratigraphic Units for Waste Injection Potential

The purpose of the hydrostratigraphic unit evaluation was to provide an objective assessment of the potential waste injection horizons and to determine which formation is considered most suitable for accepting waste fluids as a function of location. Three potential injection horizons, the Mannville Group, the Cooking Lake/Beaverhill Lake/Watt Mountain Group, and the Cambrian/Granite Wash were evaluated both independently and jointly to determine which is most suitable for waste fluid injection. The constraint mapping process was used in this evaluation to assess the areal variations in suitability.

The rationale for arriving at the rankings assigned within each formation for criteria listed in Table 3.1 are discussed in Appendix B.

It should be noted that constraint mapping is largely dependent on the accuracy and availability of existing information and therefore areas with abundant information are more easily defined than areas with little or no data (i.e., the Alberta portion versus the Saskatchewan portion of the study area for example). This fact however does not affect the qualitative nature of the mapping exercise but introduces uncertainty into the results for those areas that are poorly defined.

The results of the constraint mapping for each individual formation were assimilated by comparing the sum of the rankings or scores on a township by township basis. These results are presented in Figures 3.2, 3.3 and 3.4 which show the formations which are most suitable (i.e., scored highest), of questionable suitability and least suitable (i.e., scored lowest) for waste injection for any given location within the study area. These figures were prepared using the formation which ranked the highest for each given township. In this manner, the suitability of a formation for waste injection is relative to the suitability of other formations at the same location.

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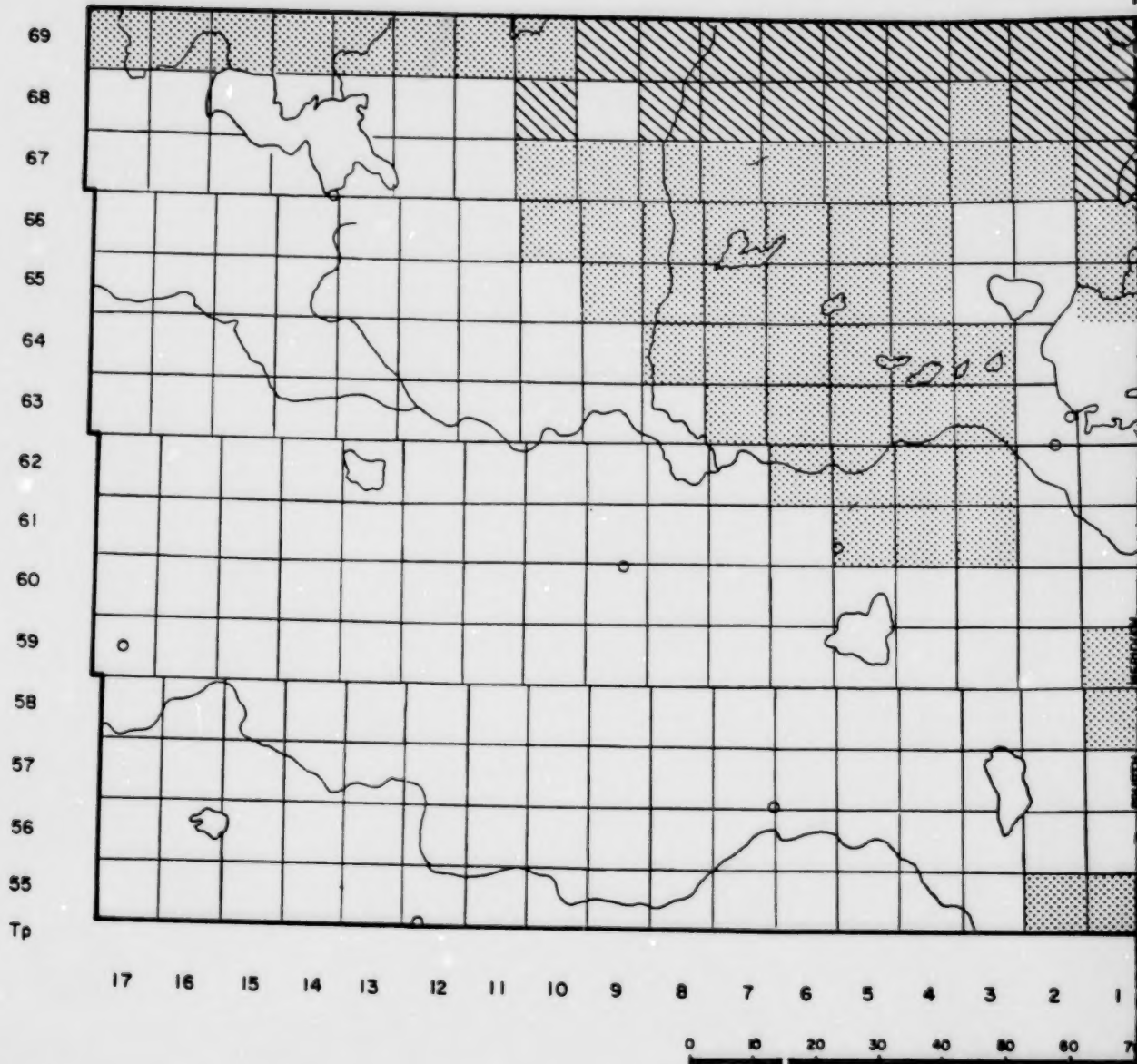
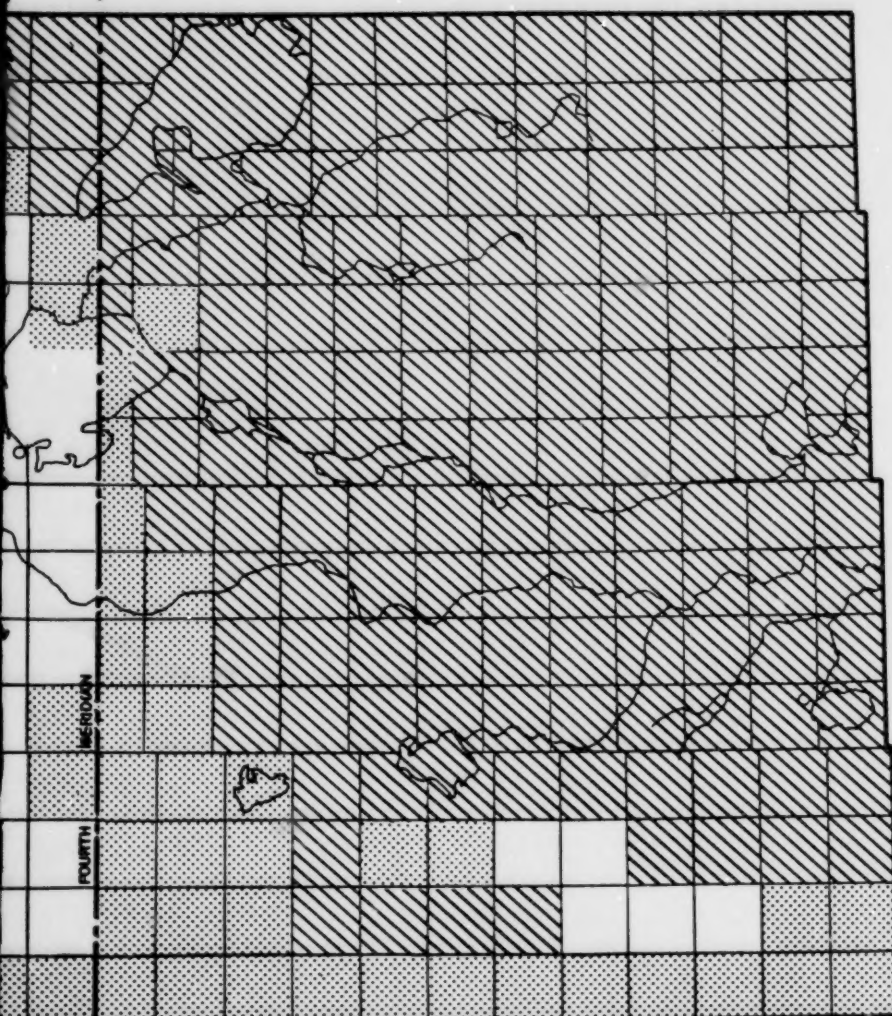


FIGURE 3-2 SUITABILITY OF MANNVILLE GROUP FOR WASTE INJECTION

SASKATCHEWAN



MOST SUITABLE FOR
WASTE INJECTION



QUESTIONABLE SUITABILITY
FOR WASTE INJECTION



LEAST SUITABLE FOR
WASTE INJECTION

1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

0 70 80 90 100 km

UP FORMATION

NOTE : IN SASKATCHEWAN, MOST OF THE MANVILLE GROUP IS WITHIN THE ZONE OF ACTIVE GROUNDWATER CIRCULATION AND THEREFORE MAY BE UNSUITABLE AS A DISPOSAL ZONE.

ALBERTA

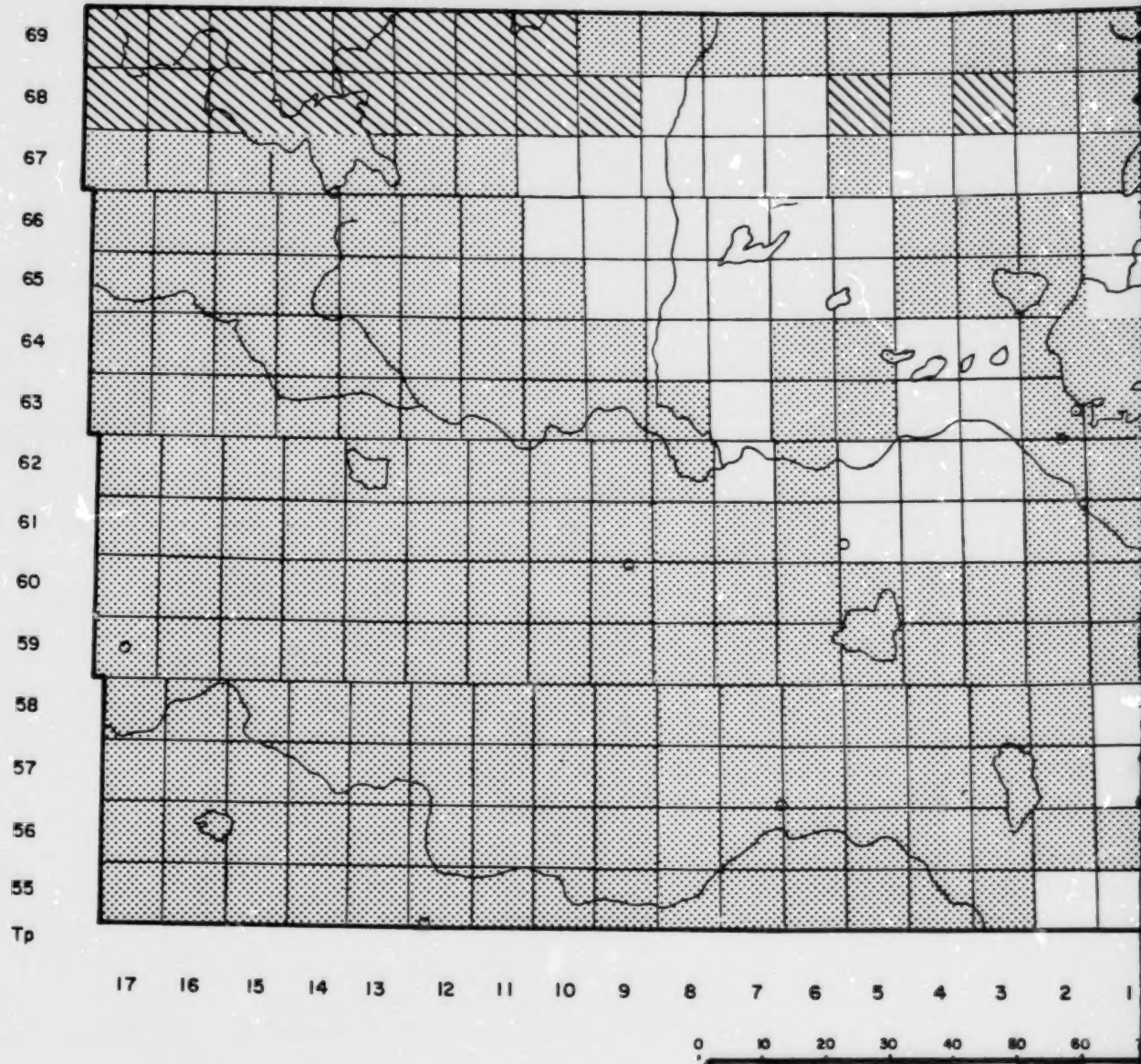
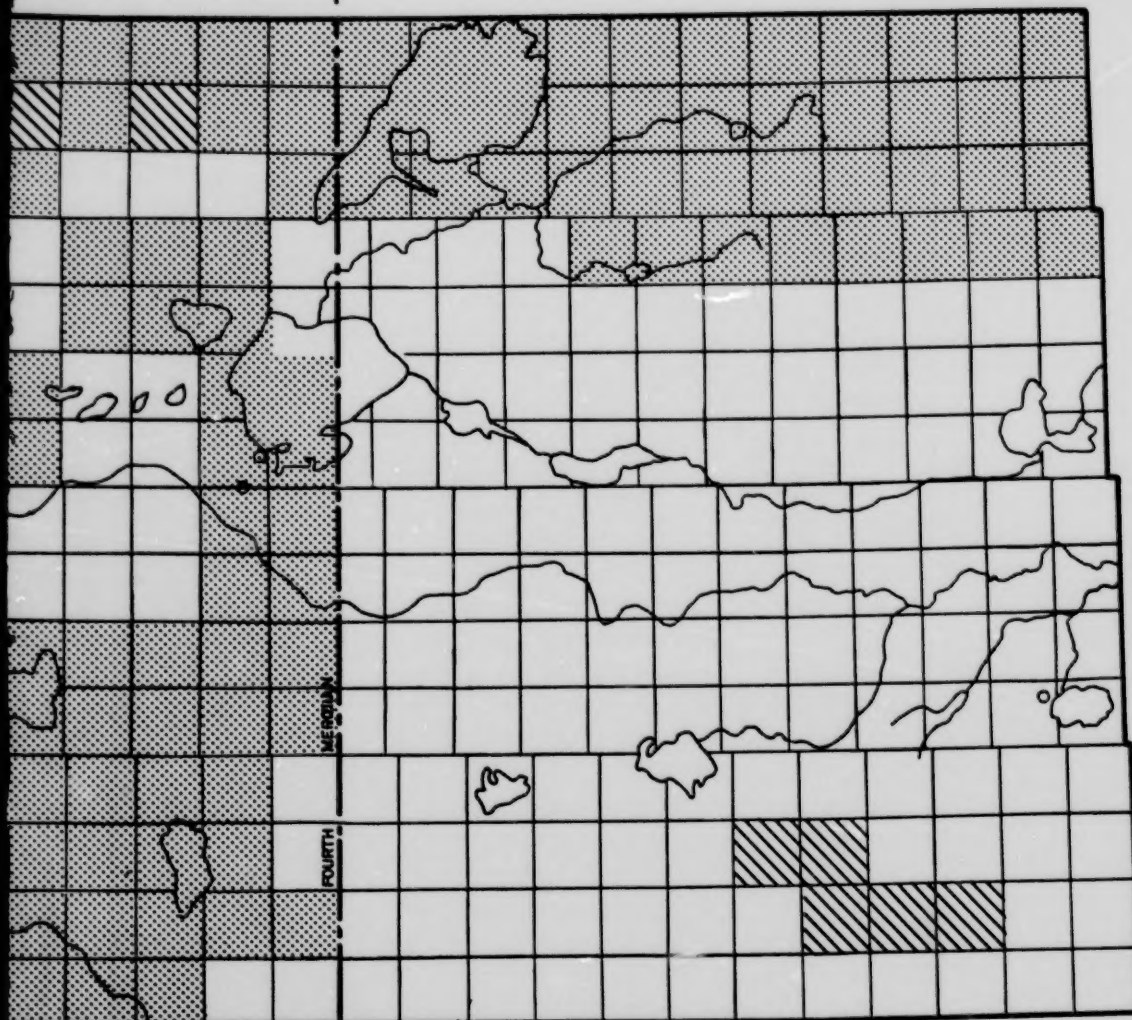


FIGURE 3-3 SUITABILITY OF COOKING LAKE/BEAVER FOR WASTE INJECTION

SASKATCHEWAN



**MOST SUITABLE FOR
WASTE INJECTION**



**QUESTIONABLE SUITABILITY
FOR WASTE INJECTION**



**LEAST SUITABLE FOR
WASTE INJECTION**

5 4 3 2 1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

30 40 50 60 70 80 90 100km

**OF COOKING LAKE/BEAVERHILL LAKE/WATT MOUNTAIN GROUP FORMATIONS
INJECTION**

ALBERTA

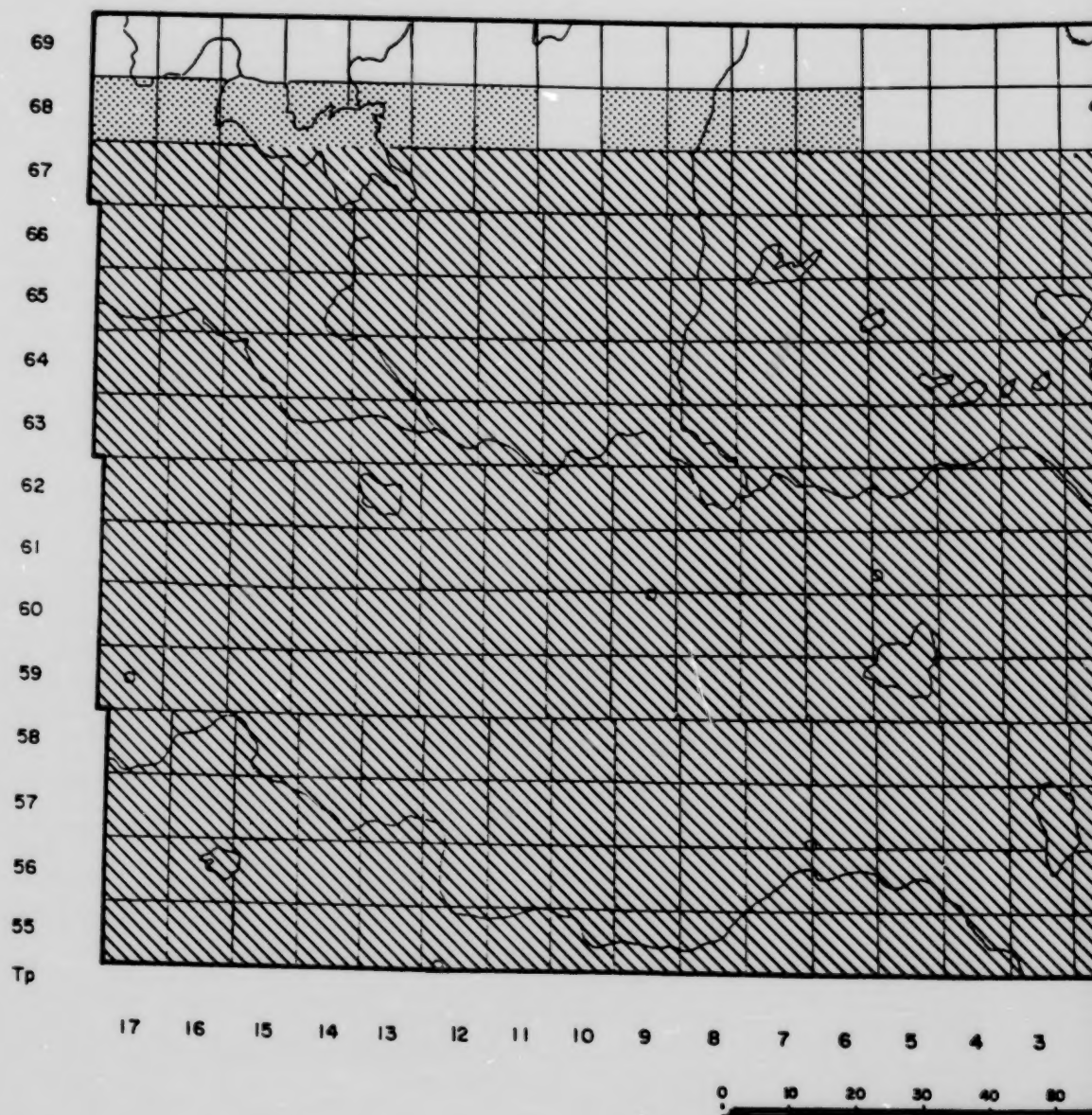
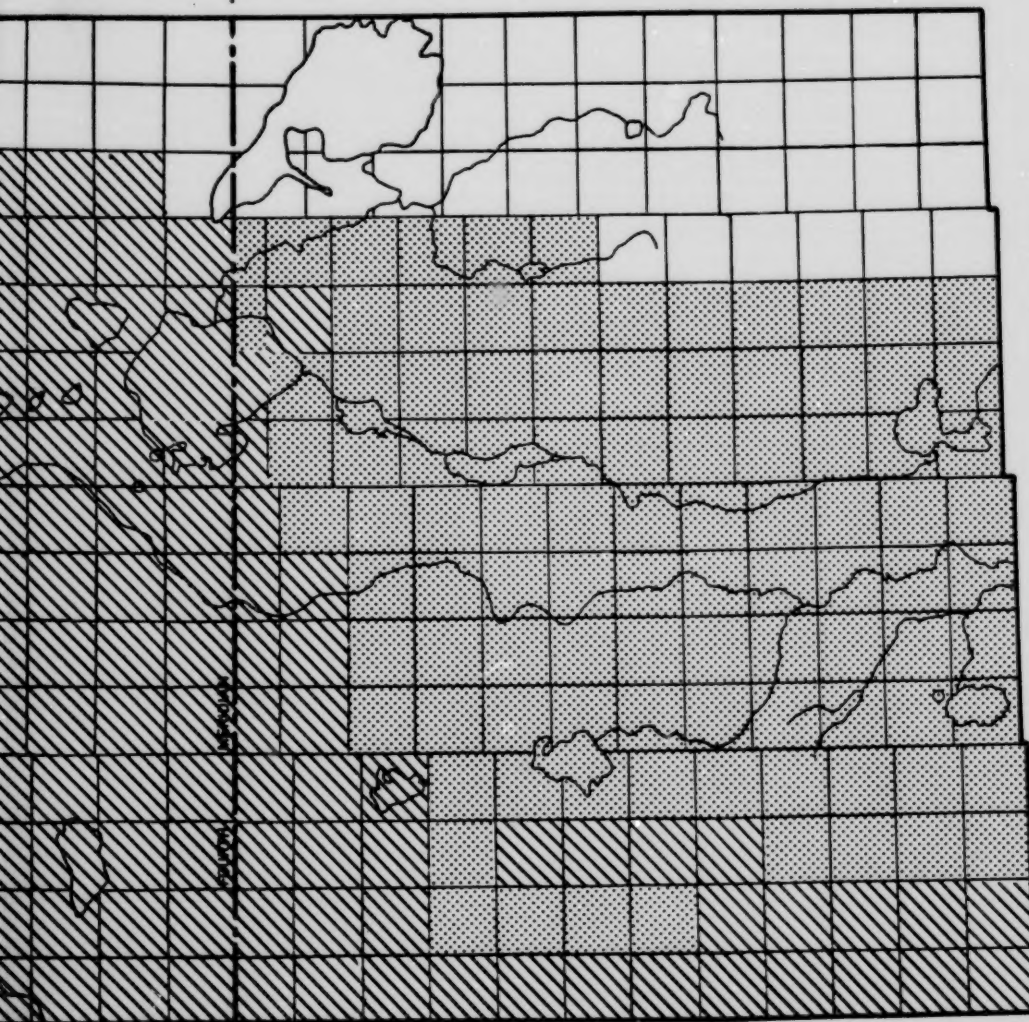


FIGURE 3-4 SUITABILITY OF THE CAMBRIAN
FOR WASTE INJECTION

SASKATCHEWAN



MOST SUITABLE FOR
WASTE INJECTION



QUESTIONABLE SUITABILITY
FOR WASTE INJECTION



LEAST SUITABLE FOR
WASTE INJECTION

3 2 1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

100 90 80 70 60 50 100 km

CAMBRIAN/GRANITE WASH FORMATIONS
ON

The results of the hydrostratigraphic unit evaluation show that of the three formations evaluated, the Mannville Group (Figure 3.2) is the most suitable injection formation throughout most of the Saskatchewan portion of the study area. However, it must be noted that much of the Saskatchewan Mannville Group is considered to be within a zone of active groundwater circulation and therefore may be unsuitable as an injection horizon. The Mannville Group area corresponds to the subcrop areas of both the CBWA and the Cambrian/ Granite Wash and where the Ireton Shale and Prairie Formation confining layers are absent. It is thought that all three candidate horizons are in close hydraulic connection in this area and possibly act as a single hydrostratigraphic unit. If this is the case, it may be acceptable to inject into the connected formations below the Mannville Group to provide a greater travel path length to surface. However, the discontinuity of these formations in this area may create operational problems in waste injection (i.e., high injection pressures). These potential problems would need to be evaluated prior to selecting a zone other than the Mannville in this area.

In the northeast portion of the study area the Mannville Group is noted as being most suitable for waste injection but it must be considered that that this designation is relative to the two other disposal formations. The CBWA and Cambrian/Granite Wash are designated either least suitable or of questionable suitability in this area. However, as noted above the Mannville Group is considered to be within the zone of active groundwater circulation (Meneley, 1983a, see Section 2.2.1.7) and vertical groundwater flow from the Mannville to overlying units may occur in some localized areas. It is, therefore, important to confirm the head relationships in the Mannville Group and overlying units in order to define the flow system before the Mannville Group is considered as a disposal horizon in this area.

The CBWA (Figure 3.3) is a most suitable injection formation in only a small portion of the study area. This is due to a number of reasons including its subcrop over most of the study area, low porosity, absence of a confining unit and the affect of structural features on its ability to contain waste fluids. These features make the CBWA of questionable suitability or least suitable for waste injection. Furthermore, the Cambrian/Granite Wash has more desirable hydraulic properties (i.e., permeability and porosity) and is present in all areas where the CBWA scores high (i.e., where the CBWA is fully intact in the southwest).

The Cambrian/Granite Wash (Figure 3.4) is the most suitable injection formation where it is confined by the Prairie Formation or where it is fully intact (i.e., south of the Meadow Lake Escarpment). This area consists of most of the Alberta portion of the study area. Throughout most of Saskatchewan the Cambrian/Granite Wash is of questionable suitability. The Cambrian/Granite Wash is absent in the northern portion of the study area.

3.2 IDENTIFICATION OF CANDIDATE FIELD MONITORING LOCATIONS

The objective of the field monitoring locations evaluation is to determine the most desirable areas for a test well and/or monitoring facilities. The objectives are further refined to encompass the need for both assessing background information and to monitor the impact of waste fluid injection. As a consequence, essentially two independent evaluations were performed: one to locate a monitoring/testing location to assess background conditions (the "background" site); and a second to monitor waste injection (the "impact" site).

Both the background and impact sites were located using a constraint mapping process similar to that used in the hydrostratigraphic unit evaluation and therefore contains the same uncertainties with regards to information levels as was noted in Section 3.1.1. However, a two-tiered constraint mapping program was adopted for the identification of candidate field monitoring locations. The first stage involves an elimination of those areas which are remote to the heavy oil reserves. The rationale for this approach is that vast tracts of land exist within the study area which are far beyond the known hydrocarbon reserves. To locate a test well or wells in these areas for the purpose of investigating waste fluid injection is unreasonable for a number of reasons. Firstly, background groundwater quality is likely to be substantially different than nearer to the existing or potential injection sites. Formation pressures are also likely different and the pressure build-up will be substantially less than nearer to the injection sites. The pressure build-up at distance will take longer to occur and will be more difficult to detect if in fact it does extend to this radial distance. In addition, in assessing the radius of waste fluid migration, a well located at great distance from the injection site will not detect waste fluids for some time (i.e., years) if at all (see Section 2.2.2.1). For these reasons, the area for detailed constraint mapping was reduced from the total study area size to incorporate only the area where known oil or gas reserves

exist as derived from ARC (1985a) and shown in Figure 3.1. This area was subsequently extended to encompass all of the area within a 20 km radius of known injection wells (Figure 2.5) which are associated with heavy oil processing. The area subsequently adopted is considered to enclose the area in which monitoring and/or test wells could justifiably be located. This area is outlined in Figures 3.5 and 3.6.

The criteria and weighting used in constraint mapping to locate both the background and impact sites are discussed in the following sections.

3.2.1 Siting of a Monitoring System to Assess Background Conditions

As discussed previously, it is desirable from a monitoring perspective to define the baseline conditions in a potential injection zone. This is desirable in that it provides a basis against which subsequent monitoring data can be judged and the impact of waste injection can be measured. Ideally, background conditions in terms of water quality and formation pressures would be quantified prior to commencement of waste injection. However, this is not possible in the area under study as waste fluid injection is currently occurring in all three of the potential injection horizons identified. In this case, sites can be selected which are relatively undisturbed or uninfluenced by waste injection operations. Although this may compromise the purpose of the background data, it will still provide valuable information which can be used in future impact assessment.

The criteria selected for siting a monitoring system to establish background conditions and the weightings assigned to these criteria are presented in Table 3.2 and discussed below.

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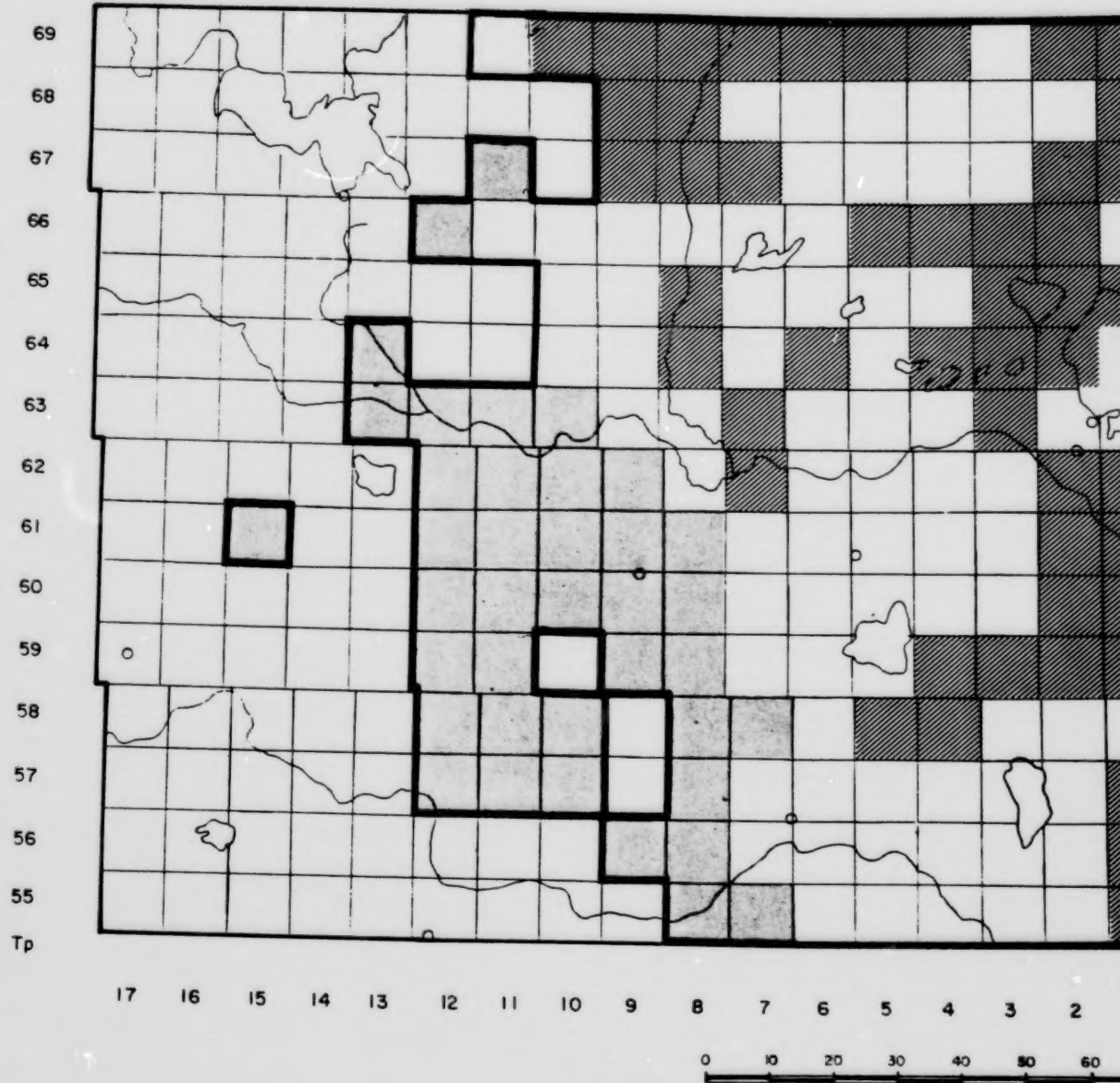


FIGURE 3-5 LOCATIONS FOR

SASKATCHEWAN

LEGEND



AREAS OF HIGH
PREFERENCE



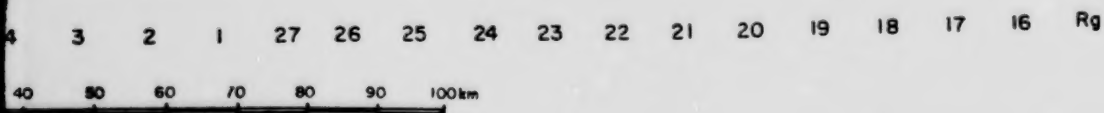
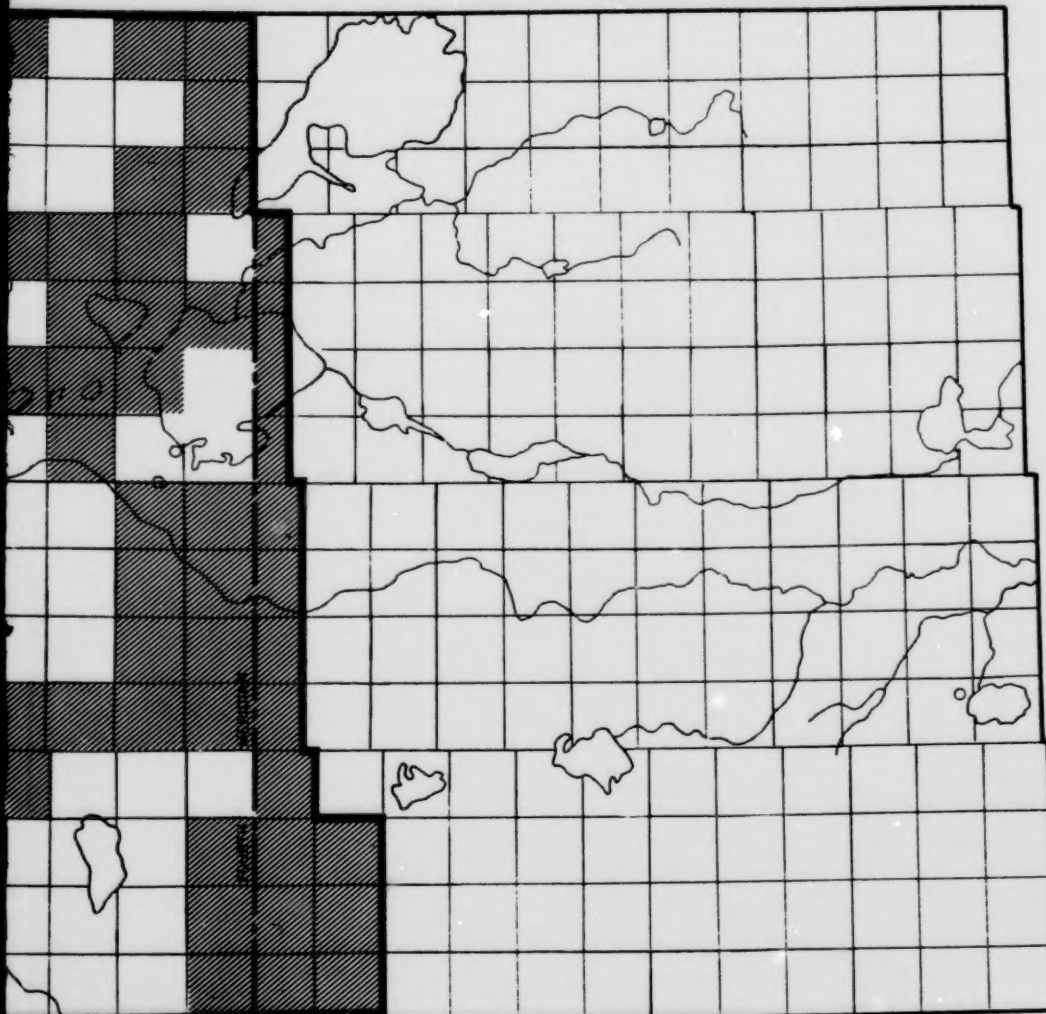
AREAS OF INTERMEDIATE
PREFERENCE



AREAS OF LOW
PREFERENCE



BOUNDARY FOR AREA OF
DETAILED EVALUATION



ATIONS FOR ASSESSING BACKGROUND CONDITIONS

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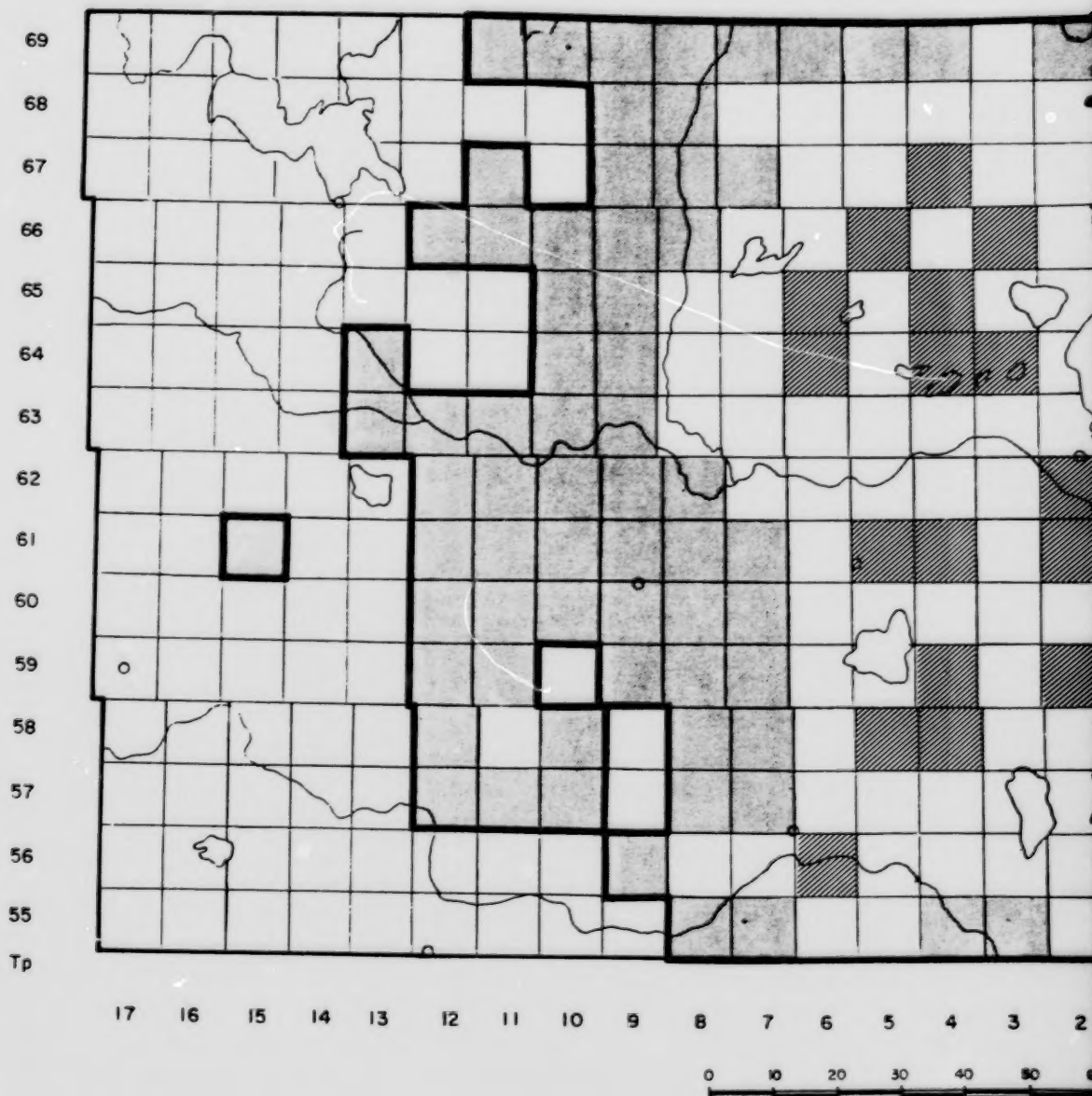


FIGURE 3-6 LOCATIONS FOR
OF WASTE FL

SASKATCHEWAN

LEGEND



AREAS OF HIGH PREFERENCE



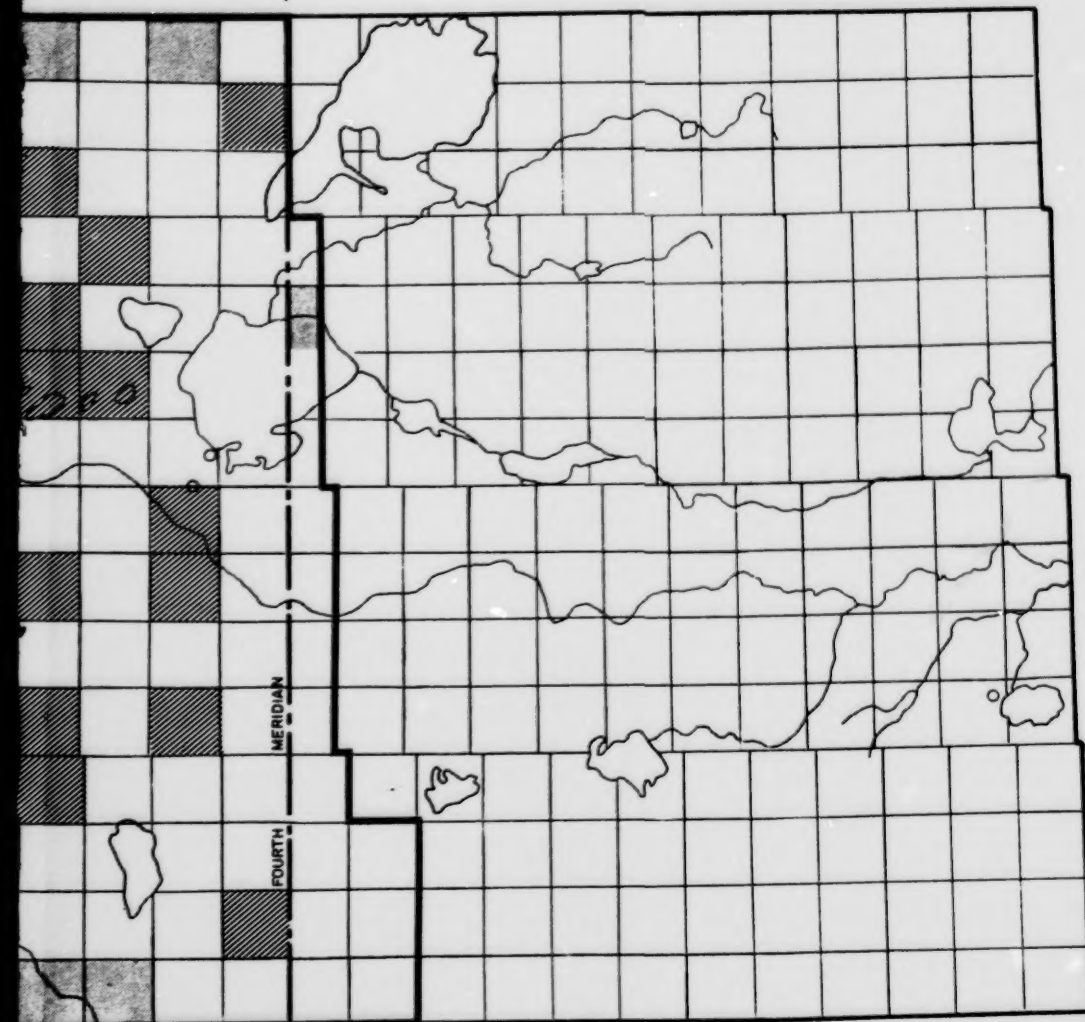
AREAS OF INTERMEDIATE PREFERENCE



AREAS OF LOW PREFERENCE



BOUNDARY FOR AREA OF DETAILED EVALUATION



MERIDIAN
FOURTH

4 3 2 1 27 26 25 24 23 22 21 20 19 18 17 16 Rg

40 50 60 70 80 90 100km

LOCATIONS FOR MONITORING THE IMPACT
OF WASTE FLUID INJECTION

Table 3.2 Criteria for Siting a Monitoring System to Establish Background Conditions

Assessment Criteria		Designation and Weighting		
<u>A. Geologic Information:</u>				
A1.	Proximity to Major Structural Influences on Groundwater Flow	0 - 5 km (1)	5 - 20 km (3)	20 km (5)
<u>B. Hydrogeologic Information:</u>				
B1.	Proximity to Groundwater Discharge Zone	0 - 5 km (1)	5 - 20 km (3)	20 km (5)
B2.	Injection Formation(s) Continuity/Area Extent	1 Continuous Formation (1)	2 Continuous Formations (3)	3 Continuous Formations (5)
B3.	Containment Capabilities/Integrity of Confining Layer(s)	Low (1)	Intermediate (3)	High (5)
<u>C. Resource Information:</u>				
C1.	Proximity to Existing or Proposed Injection Wells	0 - 5 km (1)	5 - 10 km (3)	10 km (5)
C2.	Existence of Potentially Usable Oil and Gas Wells for Monitoring Testing Purposes	No (1)	-	Yes (5)

A. Geologic Information:

A1. Proximity to Major Structural Influences on Groundwater Flow

In assessing background conditions, it is desirable to locate a monitoring site which will allow characterization of the baseline conditions in all stratigraphic units of interest. In the vicinity of major structural influences on groundwater flow, groundwaters and formation fluids from different stratigraphic units frequently mix and formation pressures become a composite of those in the interconnected formations. The data obtained are specific to that location and can not be extrapolated to areas where the discontinuity is absent. For these reasons, it is recommended that a well to assess background conditions be located at a distance from major structural influences on groundwater flow as reflected in the criteria developed (Table 3.2).

The features which were considered as major structural influences on groundwater flow are the composite of those used for the Mannville Group, CBWA and the Cambrian/Granite Wash in Section 3.1. The individual rankings assigned to each township are included in Table C-1, Appendix C.

B. Hydrogeologic Information:

B1. Proximity to Groundwater Discharge Zone

In a groundwater discharge zone, as defined for the constraint mapping (in Section 3.1), formation water quality and pressures may differ somewhat than at areas remote to the discharge zone for much the same reasons as mentioned for structural influences on groundwater flow. In the discharge zone, formation pressures are lower than at any other point in the formation and absolute values may be influenced by hydraulic connection to other formations. Also, water

quality in the discharge zone may be affected by mixing with other formation water. As a consequence, background testing/monitoring sites should be located a some distance from the groundwater discharge areas identified.

The groundwater discharge areas utilized in the study area evaluation are a composite of those defined in the hydrostratigraphic unit evaluation in Section 3.1. That is, if a township is within 0 to 5 km of a major structural influence within any one of the three potential injection zones, then the township is assigned a ranking of 1 (see Table 3.2). The individual rankings assigned to each township are documented in Table C-1, Appendix C.

B2. Injection Formation(s) Continuity/Areal Extent

Areas where the candidate injection horizons are continuous are favoured over those where they are not as it is desirable to measure background conditions where it is most likely that waste fluids will be injected. As areas where a formation is discontinuous are not desirable for waste injection, it is not recommended that monitoring/testing sites be located in this area. Furthermore, it is most desirable to locate a site where more than one and hopefully all three formations could be monitored at the one location. For this reason, areas where all three candidate formations are continuous are favoured over those where fewer are present and/or discontinuous.

The number of continuous formations was based on mapping of the individual candidate formations in Section 3.1. Rankings for each township are presented in Table C-1, Appendix C.

B3. Containment Capabilities/Integrity of Confining Layers

Background monitoring/testing sites should ideally be located where the confining units are intact and competent thus preventing complications due to interformational flow. Areas where the confining units overlying all three candidate formations are present and intact are favoured over areas where the confining layers are partially eroded (i.e., subcrop zone) or where one or more confining layers are absent. These areas were derived from the evaluation of the confining layer integrity in the previous section.

C. Resource Information:

C1. Proximity to Existing or Proposed Injection Wells

Monitoring/testing sites aimed at identifying background conditions should be located beyond the radius of influence of the existing disposal operations.

C2. Existence of Potentially Usable Oil and Gas Wells for Monitoring/Testing Purposes

In townships where oil and/or gas wells currently exist, it was considered possible that these wells could be recompleted as monitoring wells and that some limited testing may be performed. Whether or not the wells were in suitable condition (i.e., adequate cementing, intact casing), drilled through the formations of interest or available for use (i.e., permission of owner) was not assessed. This criterion was included to provide only an indication of whether or not wells existed which may potentially be utilized in a monitoring or testing program. It should be noted that the existence of wells within ranges 26 and 27 of Saskatchewan was not established. This will result in a bias towards selection of a site in the Alberta portion of the revised study area. Whether or not wells exist with a township was derived from ERCB (1977a, 1977b, 1986a, 1986b).

The results of the constraint mapping process to determine a site for monitoring of background conditions are presented in Table C-1, Appendix C, and summarized in Figure 3.5. In this figure, areas of high, intermediate and low preference are indicated within the area of detailed evaluation. The three different areas were determined by dividing the range of rankings for each township into three ranges. The lowest range was assigned a low level of preference and likewise for the intermediate and high levels of preference.

It is evident in Figure 3.5 that the preferred sites for assessing background conditions are remote to the existing locations where waste injection is occurring. Also, the more preferred sites are situated at a distance from any adverse factors or uncertainties which may complicate the groundwater flow system. As a consequence, the most preferred sites are situated primarily in the west-southwest portion of the study area. The area identified as highly preferred should be considered above other areas in locating background monitoring facilities and should be further evaluated prior to selecting a specific drill site.

3.2.2 Siting of a Monitoring System to Assess Waste Injection Impacts

In assessing the impact of waste fluid injection, it is desirable to locate monitoring facilities in locations where the majority of waste fluid release scenarios (Section 2.2.1) can be evaluated. It is with this objective in mind that the criteria for siting a monitoring system to assess the impact of waste injection were developed. These criteria are presented in Table 3.3 and the rationale for each criteria and the weighting assigned are discussed as follows.

Table 3.3 Criteria for Siting a Monitoring System to Assess Waste Injection Impacts

Assessment Criteria		Designation and Weighting		
<u>A. Geologic Information:</u>				
A1.	Proximity to Major Structural Influences on Groundwater Flow	20 km (1)	5 - 20 km (3)	0 - 5 km (5)
<u>B. Hydrogeologic Information:</u>				
B1.	Proximity to Groundwater Discharge Zone	20 km (1)	5 - 20 km (3)	0 - 5 km (5)
B2.	Injection Formation(s) Continuity/Area Extent	3 Continuous (1)	2 Continuous (3)	1 Continuous (5)
B3.	Containment Capabilities/Integrity of Confining Layer(s)	High (1)	Intermediate (3)	Low (5)
<u>C. Resource Information:</u>				
C1.	Proximity to Existing or Proposed Injection Wells	20 km (1)	5 - 20 km (3)	0 - 5 km (5)
C2.	Existence of Potentially Usable Oil and Gas Wells for Monitoring Testing Purposes	No (1)	-	Yes (5)
C3.	Number of Injection Formations being used in Township	Zero (1)	One (3)	Two or Three (5)
C4.	Volumetric Injection Rate	0 - 20 m ³ /hr (1)	20 - 100 m ³ /hr (3)	100 m ³ /hr (5)

A. Geologic Information:

A1. Proximity to Major Structural Influences on Groundwater Flow

In monitoring the impact of waste fluid injection, the test site should be located in close proximity to any major structural features affecting groundwater flow. In this way, release of waste fluids to zones other than the injection horizon can be detected by monitoring in the adjacent formations. If monitoring was to be performed at some distance from the structural discontinuity, the waste fluid release would likely not be detected.

The structural features considered in locating the impact assessment well are those identified in Section 3.1 for the Mannville Group, CBWA and Cambrian/Granite Wash (see Table C-2, Appendix C, for rankings).

B. Hydrogeologic Conditions:

B1. Proximity to Groundwater Discharge Area

It is important to locate monitoring facilities to detect the release of waste fluids. Discharge areas are defined as the areas where formation fluids flow from a particular formation. In the case of the Mannville Group, these areas are alleged to be located beneath buried valleys of Quaternary age which are major sources of potable water in the study area. Additional discharge areas for the CBWA and Cambrian/Granite Wash were identified in Section 3.1. Following this reasoning, it is recommended that monitoring wells be located in the vicinity of groundwater discharge areas as identified in Section 3.1.

B2. Injection Formation Continuity/Areal Extent

In areas where an injection formation is of limited continuity or is discontinuous, fluids are likely to either exit from the formation or flow at greater rates due to the reduced area for flow. These areas are of concern in terms of assessing the extent of waste migration and should be addressed in the monitoring program. Areas where one or more of the injection horizons are of limited continuity or are discontinuous are favoured for siting a monitoring well. The study area was evaluated based on information presented in Section 3.1.

B3. Containment Capabilities/Integrity of Confining Units

A higher potential for waste fluid release exists in areas where the integrity of the confining units is questionable. These areas, as defined in Section 3.1, are also favoured as sites for monitoring waste fluid migration and are ranked accordingly.

C. Resource Information:

C1. Proximity to Existing or Proposed Injection Wells

In assessing the nature of waste fluid migration, there are a number of reasons for situating a monitoring site close to existing injection wells. By locating a monitoring well relatively close to the injection well (i.e., less than 5 km), the arrival and subsequent temporal changes in the position of the waste fluid plume can be monitored. Also, the pressure build-up due to fluid injection decays exponentially as the radius from the injection well increases. At large distances, it may be difficult to attribute fluctuations in pressure solely to injection due to other possible sources of the pressure anomaly (i.e., atmospheric pressure changes). Monitoring well sites within 5 km of an injection well (Figure 2.5) are preferred.

C2. Existence of Potentially Usable Oil and Gas Wells for Monitoring/Testing Purposes

The same rationale for this criteria exists as for locating a background monitoring well (see Section 3.2.1).

C3. Number of Injection Formations Being Used per Township

It is desirable to locate a monitoring well where the maximum amount of information will be acquired regarding possible effects. Thus, areas where two or three of the potential waste injection zones are in use are favoured whereas areas where no injection is occurring are ranked low. The location of existing wells is shown in Figure 2.5.

C4. Volumetric Injection Rate

Injection rates vary at different wells and the number of wells per unit area varies over the study area. Given the high cost and level of effort of developing monitoring facilities, it is advisable to locate the facilities where the need is highest. The need for environmental monitoring arises over the concern that waste fluids may be released to the near surface environment. An indicator of the risk of release is the volumetric injection rate.

Volumetric injection rates were tabulated for each injection well (Figure 2.6) and summed within each township for all formations. The flow rates were obtained from ERCB (1986, Appendix A) and are the latest monthly injected volumes divided by the duration of injection as of April, 1986. It should be noted that the injection period is not the same for all wells. However, these values likely provide the best documentation of waste fluid injection rates that are available.

The results of studies to identify preferred locations for impact monitoring facilities are summarized in Table C-2, Appendix C as a total of the numerical rankings and in Figure 3.6 as areas of high, intermediate and low preference. In Figure 3.6, areas of high, intermediate and low preference were identified in a manner similar to that described in the previous section. In this figure, the areas of greatest preference are located close to existing disposal wells. These areas should be given highest priority to ensure that monitoring facilities are within the radius of influence of waste injection. Areas of intermediate preference which scored relatively high within the intermediate range and are close to existing disposal wells are also worthy of consideration. Areas of low preference are far beyond the anticipated radius of either waste fluid migration or pressure build-up and are not expected to be affected by disposal operations.

3.3 FIELD TESTING METHODOLOGIES

3.3.1 Geologic Programs

In designing the geologic programs, it is assumed that there exists an extensive data base of geologic information from petroleum industry and government records (i.e., ERCB and SEM) and previous Alberta Research Council studies. It is not the purpose of the geologic program to design methods to examine existing data (although it is recognized that the existing data are an important source of information) but rather to design methods to collect new data from the drilling of new boreholes.

The geologic programs are therefore designed to provide site specific information and confirmatory geologic data from new boreholes in the form of:

- Stratigraphic Sequence/Geologic Column;
- Formation Rock Type;
- Formation Thickness;
- Formation Dip and Direction;
- Structural Geology;
- Mineralogical Data.

The geologic program, in addition, provides access through boreholes to subsurface formations for the purpose of geophysical, hydrogeologic and geochemical testing.

The geologic program consists of the following phases:

- Drilling Program;
- Formation Sampling and Borehole Logging;
- Lithologic Description;
- Additional Geologic Studies;
- Stratigraphic Interpretation.

These phases essentially describe a geologic sampling program. The drilling program represents the sampling methodology with the drill core being the collected sample. The sampling procedure is described by a borehole drill log while a lithologic description describes the sample. Additional geologic information is collected by conducting various tests on the core. Finally all the sampling information is integrated into a stratigraphic interpretation that describes the borehole geology.

3.3.1.1 Drilling Program. Drilling into deep formations is a complex but fairly routine procedure in the oil fields of Western Canada. It is not the purpose of this section to describe a step-by-step drilling procedure but rather to provide brief descriptions of the preferred methods and the advantages and disadvantages of each.

The preferred drilling method is by hydraulic mud-rotary techniques. The method consists of cutting a borehole by the rotation of a drilling bit and removing the cuttings by the continuous circulation of a drilling fluid. Hydraulic rotary techniques have been in use since the 1930's and are the industry standard. The method is fast and economical and capable of drilling wells in excess of 2000 m. The hydraulic rotary method is preferable over the air-rotary method because the latter requires stable formations to prevent the loss of the borehole by caving. Stable formations are not likely to exist within the current study area.

The most important aspect of the hydraulic rotary drilling method is the selection of the drilling fluid. The drilling fluid is used to support the borehole and prevent caving, to prevent fluid loss by sealing the borehole wall, to remove cuttings from the borehole and to lubricate and cool the drill bit. The selection of an appropriate drilling fluid is often dependent on borehole conditions such as borehole stability, the presence of salt formations and hydraulic pressure. Most drilling fluids consist of a clay material (usually

bentonite) and a water supply. The water supply may be fresh water, or brine depending on the formation. In salt formations, the drilling fluid is required to be a brine fluid to prevent dissolution of the formation. The addition of additives to the drilling fluid are often used to change the composition of the fluid. The most common additives (i.e., barite) are used to increase the specific weight of the fluid. Other additives such as starch and high viscosity cellulose are used to increase the viscosity of the fluid.

In the use of drilling fluids, it is necessary to monitor the properties of the fluid during drilling to ensure that the fluid is performing its essential functions. Fluid properties regularly monitored by the mud engineer include properties such as density, viscosity, gel strength, filtration property and sand content (Table 3.4). If a drill water tracer program (see Section 3.3.3.2) is used to aid in collecting geochemical samples, the tracer concentration is also included. These measurements are usually conducted several times per day to document the drilling fluid composition and ensure the proper composition.

The drilling technique should provide a minimum borehole diameter 15.2 cm (6 inch). This diameter is suitable for all hydraulic testing and geochemical sampling techniques. Larger diameter boreholes for the installation of casing can be achieved by reaming tools.

Surface casing should be installed through all fresh water zones. The specific requirements are typically specified by government regulatory bodies within their jurisdiction. As a general rule, surface casings should extend through the entire fresh water zone or about 10% of the total depth of the borehole, whichever is greater. Initial casing diameter should be of sufficient diameter to allow for several additional casings of smaller diameter.

Table 3.4 Drilling Mud Report

Company:		Contractor:		Date:
Address:		Address:		
Well:		Concession:		
Name and Number:		Township and Range:		
Operation:		Casing:		
Depth:		Surface Casing:		
Hydraulic Pressure:		Intermediate:		
Bit Size:		Last Casing:		
Mud Type:		Mud Volume:		
Temperature:		Pits:		
Time of Test:		Circ. Vol.:		
Weight:		Mud in Storage:		
Viscosity Funnel:		Tour Treatment with:		
Filtrate:		Bentonite:		
Cake Thickness:		CMC Low., Mod., or Hi. Visc.:		
HI - HP Filtrate		Chrom - Lignit:		
pH:		Ferro - Chrom - Ligno - Sulphonat:		
Sand Content:		Caustic Soda:		
Salt - Chloride:		Other:		
Alkalinity of Filtrate:		Oil:		
Calcium Content of Filtrate:		Deformer:		
Calcium Content of Mud:		Salt:		
Total Hardness:		Baroid:		
Magnesium Content of Filtrate:		Tracer Type:		
Apparent Viscosity:		Tracer Concentration:		
Plastic Viscosity:				
Yield Value:				
Initial - 10 mm Gelstrength:				
Solids Content:				
Water Content:				
Oil Content:				
Sulphate:				
Mud Cost - Daily:		Cumulative:		
Mud Properties Specifications:				
Weight:	Viscosity:	Filtrate:		
Remarks:				
Signature:				

It will also be necessary in the drilling program to collect core samples through important formations. The suggested coring method is by using a diamond-bit wire-line core barrel technique. The cored formations should include all disposal zones and confining layers. Core diameter will be dependent on borehole diameter but should not be less than 5 cm diameter. Coring should be continuous over the interval of interest at a core recovery of at least 75%.

Drilling procedures should ensure the safety of all personnel by using industry accepted safety standards. All drill rigs should be equipped with blow out preventers of suitable working pressure to contain any formation gases or fluids.

3.3.1.2 Formation Sampling and Borehole Logging. A drilling program is a geologic sampling technique and the record of sampling is provided by the geologic borehole log. A complete description of the drilling procedure, borehole drilling fluids, stratigraphy, borehole testing methods and sampling techniques from the start of drilling until the final depth should be found within the borehole log.

An example borehole drilling log is given in Table 3.5. Most of the categories are self-explanatory however several need brief descriptions.

The upper blanks provide the borehole identification and description of the drilling company and drilling technique (i.e., NX diamond drill core and mud rotary). Casing installation is described in terms of its diameter and total depth of installation below surface.

The lower columns are used to describe the day to day and metre by metre progress of the drilling program. Drilling date is recorded at the appropriate depth at the start of each drilling day. Often, breaks or delays in the drilling program are indicated by

Table 3.5 Borehole Drilling Log

Project: _____ Location: _____
 Borehole: _____ Orientation: _____
 Drilling Co.: _____ Drillers: _____
 Drilling Period: _____
 Datum Elevation: _____ Datum Reference: _____
 Drilling Technique: _____ Depth: _____
 : _____ Depth: _____

Geologist: _____

Casing: Diameter _____ Depth _____
 Diameter _____ Depth _____
 Diameter _____ Depth _____

Page _____ of _____

[illegible]

several dates (or times) at the same depth. Depth below surface is measured from the reference datum, usually the well casing or drill platform, at a scale of 1:200 (i.e., 1 cm = 2 m) down the drill log to provide a continuous record of the drilling. Bit diameter is the diameter of the drilling bit or the casing shoe. Notes regarding changes in the drill bit or borehole reaming are recorded here. Drilling fluid data are recorded as measurements or changes are made. Information such as drilling fluid composition, fluid specific gravity, mud type, mud additions, mud circulation losses, drill tracer concentrations and drill fluid samples are recorded in this column. Borehole testing data are recorded in detail at the appropriate depth of testing. Notes on testing include the type of testing (i.e., drill stem testing, geophysical logging, or geochemical sampling) date of testing, test interval depth and important test data (i.e., high permeability zones, geophysical anomalies, etc). Drilling rate in minutes per metres is recorded as a bar graph as drilling proceeds. The drilling rate provides an indication of the hardness of the formations. Core recovery, if coring is the drilling technique, is recorded as a fraction and a percentage of the total core run or it can be illustrated graphically. Also from the core, the number of fractures per metre of core is recorded. The profile column is used to pictorially represent the borehole stratigraphic column. Each rock type (i.e., sandstone, shale, limestone, etc.) is illustrated by symbols or patterns. Geologic features such as fossils, nodules, concretions, crystals, vugs, unconformities, dipping beds, sedimentary structures, faults, etc. are drawn in at orientations and depths as found in the core. The lithologic description is the most important column in the drill log as it provides the geologic description of each stratigraphic unit as it is intersected. Procedures for the lithologic description are given in the next section. Details such as rock type, colour grain size, texture, structure and mineralogy are described in detail in this section. The final column of the borehole log is used to describe additional information such as water quality results (i.e., electrical conductivity, salinity of borehole fluids), geotechnical

information (i.e., fracture orientation, rock quality) sampling notes or general comments about the drilling procedure. When the borehole drilling log is completed, it and the drill core (or chip samples) form the complete record of the drilling program.

Drill core requires special considerations in a drilling program as it is as valuable a source of information as the drill log. The drill core should be stored in special boxes for that purpose. Each core box should be labelled (on top and ends) with the date of drilling, borehole name and location, borehole interval and geologist's name. Inside the box, the core should be laid out as removed from the core barrel. Pieces of core should be assembled as best as possible to resemble the original structure. The beginning and end of each core run should be labelled and lost core sections identified. All notes regarding the core should be entered onto the drill log. If core samples are removed for testing (see Sections 3.3.1.2, 3.3.1.3 and 3.3.1.4), notes should be entered on the drill log and into the core box.

Chip samples resulting from the action of the drill bit provide less detail as compared to drill cores but indicate the general stratigraphy, changes in lithology and formation thicknesses. The logging of chip samples requires attention and considerable experience to provide reasonably representative samples. Chip samples are generally mixed to some degree with rock fragments from other parts of the borehole. Identification of changes in lithology are determined from the first appearance of chips from that formation. Where changes in formations are gradational, the chips may have to be compared or examined by microscope to provide the required detail. Chip samples are usually collected at every 1.5 or 3.0 m intervals, washed thoroughly, dried and then placed in dust-proof bags. Each bag should be labelled with the borehole identification, logger's name, borehole interval and the date. If the depth is corrected for the time to reach surface this should also be noted.

3.3.1.3 Lithologic Description. In the construction of the borehole drill log and the examination of the core, it is necessary to provide an adequate lithologic description. The following discussion details the information required in the lithologic description, and the methods of interpretation. The lithologic description of a sedimentary rock delineates its texture, sedimentary structure and composition which in turn is used in the interpretation of the stratigraphy.

(1) Texture

In the lithologic description is found details of the sedimentary textures. Texture refers to the characteristics of the sedimentary particles and the grain-to-grain relations among them. In general, the texture is determined by the size and shape of the particles and their arrangement in the aggregate. Five properties of the particles generally define the texture of the sediment: size, shape, roundness, surface texture and orientation. The size of particle provides an indication of the dynamic conditions of sediment transport and deposition. Grain size is a commonly measured textural parameter that is always reported in the lithologic description. Related to grain size is the uniformity of sorting of the grain size distribution. Shape of particle and particle roundness similarly provides an indication of transport and deposition condition. For example, angular fragments have not been strongly abraded and indicate a short transit from the source to deposition. Surface texture is indicative of the particle abrasional history or it may reflect post depositional changes. Orientation of particles determines the fabric or packing of the aggregate which in turn determines such properties as porosity.

Textural features such as those described above are also found in chemical and nonclastic rocks; however, the implications to stratigraphic interpretation are not as well defined. In many cases, textural features in these rocks are indicative of physical and chemical condition during or after deposition.

(2) Sedimentary Structure

Sedimentary structures, although typically large scale features are often found in drill cores and are noted in the lithologic description. These structures are commonly found contemporaneously (syngenetic) with the sediment or after deposition (epigenetic). Syngenetic structures often seen in cores include cross-bedding, graded bedding ripple marks, flute casts, load casts, slump features, biostromes and fossils. Epigenetic structures include such features as folds and faults, conformable or nonconformable boundaries, concretions and crystal molds and casts.

Structural features should always be noted in the lithologic description in sufficient detail to provide stratigraphic information. Details such as relative dip of beds, direction of grading, nature of boundaries and orientation of fossils should always be included in the borehole logs. Of particular importance in these descriptions of sedimentary structures are formation contacts and structural faults or fractures. The formation contacts will likely define hydrogeologic and stratigraphic units that are important to disposal well practices.

(3) Mineralogical and Chemical Composition

In the lithologic description, composition is commonly given first ranking in the classification of sedimentary rocks. Details of the mineralogical and chemical composition of the sediment is typically one of the most important descriptive parameters in the study of sedimentary rocks.

The mineralogic composition of sedimentary rocks is largely determined by the composition of the source material or by chemical evolution during or after deposition. Detrital minerals are those broken or abraded particles brought to the depositional site by mechanical transport. Minerals such as quartz, clay minerals and fine

micas are most dominant in this group with chert, feldspars and coarse micas in lesser amounts. Nondetrital minerals are precipitated from solution during or after deposition. The most common minerals in this type are calcite and dolomite.

Mineralogical composition can generally be determined in the field using a binocular microscope. For the purposes of lithologic descriptions the mineralogy should be described in terms of the major and minor components with estimated percentages. More detailed descriptions of the mineralogic composition can be determined by x-ray diffraction (see Section 3.3.1.4).

Chemical composition of most rocks is difficult to determine in the field and usually requires analytical methods. However, in some cases, for coarse grained rocks, the chemical composition can be estimated based on the mineralogic composition. For lithologic descriptions, the chemical composition should be noted where it can be determined. Examples of obvious chemical composition are: carbonate content in calcite and dolomite (generation of gas in an HCl acid test); iron in red and green shales; iron or organic carbon in black shales; and sodium and chloride in salt formations. Detailed geochemical analysis can be conducted on cores at a later date to determine exact chemical compositions.

3.3.1.4 Addition Geologic Studies. The collection of core samples in the drilling program provides the opportunity to conduct additional geologic studies to enhance the lithologic descriptions.

Five core studies have been chosen as follows:

- Grain Size Analysis;
- Thin Section Studies;
- X-ray Diffraction;
- Carbonate Analysis;
- Cation Exchange Capacity.

Although these studies are not routinely conducted in oil field investigations, they are of particular importance in geochemical and hydrogeological studies because they provide the physical characteristic of the formations (i.e., mineralogical and chemical composition). These additional studies have been chosen because of the benefit of the information gained and relative ease of application.

Grain size analysis is perhaps the most common study conducted on clastic rocks. It is widely used to determine dynamic conditions of sediment transport and deposition. Several methods can be used to determine the grain size distribution of sediments including visual inspection, mechanical sieving and settling velocity methods. Each method essentially determines the size distribution of the clastic particles. Consolidated and cemented clastic rocks must be broken down into individual particles prior to analysis. Grain size analysis provides information on sorting, porosity, and permeability. Clastic samples from all zones of interest should be analyzed for grain size.

Thin section studies are routinely conducted in sedimentary petrology to provide a more detailed mineralogic description than can be determined in hand specimens. Thin sections are prepared by cutting and polishing thin slices of core and mounting the slices on glass for examination by a polarized light microscope. Polarized light enables identification of specific minerals by examination of each minerals refractive properties. Mineralogic composition is determined by mineral identification and estimating the percentage of each mineral. Thin section studies also provide information on porosity, grain cementing and rock type. It is recommended that thin sections be examined for a number of important zones (i.e., disposal zones and confining layers) with thin sections aligned parallel and perpendicular to the bedding planes.

X-ray diffraction analysis of core samples is another method of determining the mineralogic composition of core samples. This method can be used on whole samples or sieved grain size fractions to determine the major and minor components of the rock units. X-ray diffraction is especially useful in identifying the composition of fine grained sediments especially clay minerals. It is recommended that x-ray diffraction analysis be conducted on a representative number of samples especially in zones of interest (i.e., disposal zones and confining layers).

Carbonate formations are likely to be found in the geologic column. Simple techniques can be used to accurately determine the carbonate composition of these rocks. The method entails grinding the rock to powder then adding hydrochloric acid. Carbon dioxide gas is liberated at a rate that is proportional to the calcite to dolomite ratio and at a volume that is proportional to the total carbonate content. This method is especially useful to distinguish between limestone and dolomite and for estimates of the buffering capacity.

Cation exchange capacity (CEC) is a useful geochemical parameter in contaminant hydrogeology studies that can be conducted on core samples. CEC is usually measured and defined by the uptake and release of ammonium ions from an ammonium acetate solution at a pH 7.0. Clay minerals, colloidal oxides and organic matter all exhibit ion exchange behavior to some degree. Ion exchange reactions will have an important control on water chemistry whenever water is in contact with these exchanging sediments. It is recommended that CEC be determined on a number of core samples in the geologic program.

3.3.1.5 Stratigraphic Interpretation. The culmination of the drilling and logging program, lithologic description and additional geologic studies is the stratigraphic interpretation of the borehole geology. The stratigraphic interpretation provides the classification of the stratigraphy in terms of rock - stratigraphic units as well as descriptions of the geologic environment, formation paleontology and structural geology. The stratigraphic interpretation is usually completed in a separate report with important details such as formation names and time units transferred to the drilling log.

The classification of the stratigraphy is generally completed based on rock-stratigraphic units which are distinctive rock bodies identifiable over large areas. Typically these units are of a single rock type (i.e., shale, sandstone, etc.) but may also be intercalations of several types (i.e., shales and limestones). The units are lithologically distinct and defined by observable contacts. Rock-stratigraphic units are generally described in terms of formation or groups (i.e., McMurray Formation of the Mannville Group).

In the stratigraphic interpretation of rock, stratigraphic units are determined by comparison to the lithologic descriptions of type sections or the known geologic columns for adjacent boreholes. Lithologic descriptions, correlations between rock sequences, key bed locations or unconformities can be used in the designation of rock units. Attempts should be made to define and classify all members, formations and groups for the geologic column in the Cold Lake area (i.e., Figure 2.1). Rock types should be given formal names where possible. Formation thickness or apparent thicknesses should be defined based on contacts or unconformities.

Associated with the classification of the lithology is the interpretation of the geologic environment. This interpretation can be derived from existing historical geology reports or interpreted from the stratigraphy. The geologic environment should include discussions of the genesis of the stratigraphy, source materials, transport distances, and depositional conditions (i.e., deep or shallow water, fresh or sea water, etc.). Interpretation of the geologic environment provides the correlation between formations and the regional geologic structure.

The formation paleontology is used to interpret time-stratigraphic units. Time-stratigraphic units are sequences of strata that were accumulated over a particular geologic time. They are usually identified by fossil assemblages and comparisons to time-type sections. The identification of fossils within each formation is a complex procedure, however, attempts should be made to identify important fossil types in the stratigraphic interpretation.

Structural geology is considered important in the stratigraphic interpretation because of its significance in hydrogeology. Features such as faults, fractures, reefs and collapse structures may enhance groundwater flow or control the hydrogeology. Faults require interpretation in terms of orientation, movement, continuity, age, and associated fracturing. Faults are often associated with shear zones which may be more permeable than the surrounding formations. Similarly fractures will be found in most formations. These features should be interpreted in fracture sets depending on dip (i.e., horizontal, vertical, subvertical, etc.). Where possible, the orientation of fractures may be determined from comparison with known formation orientations. Fractures, like faults may be significant hydrogeologic features and notes regarding fracture aperture, orientation, continuity and lost circulation zones should be included in the stratigraphic interpretation.

Reefal structures (carbonate mounds, pinnacle reefs) usually have good porosity and permeability. These features may control groundwater flow in their area. In the interpretation of the reefal structure, dimensions of the structures, nature of boundaries and estimated porosity and permeability provide valuable hydrogeologic information.

Collapse structures associated with the dissolution of salt formations are important structural features that should be explained in the stratigraphic interpretation. Salt solution produces irregularities in the thickness and structure of younger deposits. These features are often quite local and may lead to anomalous estimates of formation thicknesses. Fracturing results from dissolution may also increase the permeability of overlying formations.

3.3.2 Geophysical Logging

A number of geophysical testing techniques exist which provide information useful in studies of a hydrogeologic and geochemical nature. In this section, the following geophysical techniques are reviewed:

- Electric Logs;
- Radioactive Logs;
- Elastic Wave Propagation Logs;
- Mechanical Logs.

These logging techniques are discussed in terms of the information provided by each technique, the factors affecting the performance of the technique and how the logging results compare between the various techniques. Much of the following discussion has been based on a review of downhole geophysical techniques by the Earth Technology Corporation (ETC, 1985) as well as through contact with experts in the area of geophysical studies.

3.3.2.1 Electric Logs. Electric logs are useful in making inferences on the properties of geologic media and formation water based on correlations with their inherent electrical characteristics. These logs are run in open boreholes only and cannot be run in cased holes.

Single point logs, including self potential and resistance logging are common in both the oil and water well industry and are useful when interpreted jointly with geologic logs. Resistance logs have been used to locate major fracture zones although smaller fracture zones and discrete fractures are not usually identifiable (Davison et al., 1982a). These logs also provide a qualitative indication of relative porosity and an indication of changes in lithology.

Self potential or spontaneous potential (SP) logs measure the naturally occurring potential differences between the downhole and surface electrodes which arise due to electrochemical interactions between the borehole and formation fluids. SP logs provide an indication of lithology, bed thickness, formation porosity, water quality and fracture zones.

The main limitations on both types of single point electric logs are that they are qualitative in nature. They have only a shallow radius of investigation and they are affected by borehole diameter and borehole fluid resistivity (Dyck et al., 1972 in Freeze and Cherry, 1979). However, it is noted that resistance logs are generally quite useful if the ratio of the formation to mud resistivity is less than 10 (ETC, 1985).

Resistivity or Normal Resistivity logging consists of lowering, downhole, a multi-electrode system which consists of at least one current electrode and two measuring electrodes. In this way, a quantitative assessment of formation resistivity is obtained for the area immediately around the borehole (ETC, 1985). The radius of the measured area is generally twice the electrode spacing which, in

conventional electrode configurations, results in a measured radius of either 32 or 128 inches. Resistivity logging is most appropriate in lower resistivity formations although this is a function of borehole fluid resistivity relative to that of the formation as well as the electrode spacing. Resistivity logging can provide significant information on fracture occurrence, changes in lithology, water quality and formation porosity. It is expected that the formation fluids, being high in conductivity (low resistivity) would dominate the measurements for the study area of concern and that the drilling fluid used would be of low resistivity relative to formation fluid in order to not compromise the test results. This criteria on drill fluid is important particularly when using salt-saturated brines.

A more recent development in electric logging is the use of focused resistivity logging which was originally developed to overcome the limitations of normal resistivity logging. Focused resistivity logging involves the use of guard electrodes which force the current out in a direction perpendicular to the electrode as opposed to the spherical distribution created during normal resistivity logging. The method provides essentially the same information as for normal resistivity logging with the advantage that the measurement area is essentially horizontal (as opposed to spherical) and a greater depth of penetration is achieved. These advantages make focused resistivity logging much more desirable than either resistance or normal resistivity logging (Heffernan, 1986).

Induction logging is based on the formation's and fluid's electrical conductivity. The method induces a current in the subsurface through the creation of an electromagnetic field at the downhole tool. Secondary magnetic fields are consequently set up and induce a voltage in a receiver coil proportional to the electrical conductivity in the region of the borehole. Induction logs are reportedly the best method of obtaining resistivity measurements in a borehole (Watt, 1974 in ETC, 1985). Induction logs are most

appropriate for measuring low resistivity (high electrical conductivity) formations (generally less than 200 ohm-metres) due to the dependence of the method on conductivity measurements. Induction logging is also useful in identifying changes in lithology and mineralogy as well as providing an indication of porosity. This type of logging is best suited to the situation of a lower resistivity in the formation relative to the borehole (typical of fresh water muds). These criteria are typically met in sedimentary basins which have inherently high total dissolved solids in formation waters particularly at depth.

Dual induction logs, consisting of a spherically focused induction log and an SP log, are considered to provide optimal data from any two electric logs (Heffernan, 1986). These logs are performed at the same time and are commonly used in the oil industry. As a result, it is recommended that dual induction logs be performed as part of the geophysical program for uncased holes (see Table 3.6).

3.3.2.2 Radioactive Logs. Natural gamma or gamma-ray logs are based on measuring the naturally occurring gamma radiation inherent in the rock surrounding the borehole. Natural gamma logs thus provide an indication of changes in mineralogy and lithology. These logs are useful in identifying the location of fracture zones by detection of either the lower radiation emanating from the fracture filling fluid or the different radiation levels emanating from secondary mineral precipitates as compared to the rock mass. Natural gamma logs also provide an indication of porosity.

Natural gamma logs are common in the oil industry and are frequently interpreted in conjunction with neutron logs (to identify fracture zone trends), caliper, sonic, neutron and gamma-gamma logs.

Table 3.6 Geophysical Logging Recommended for Both Cased
and Uncased Boreholes

Logging Method	Uncased Borehole	Cased Borehole
Electric Logs		
Focused Induction	X	
Spontaneous Potential	X	
Radioactive Logs		
Compensated Neutron	X	X
Natural Gamma	X	X
Gamma-Gamma (Density)	X	
Elastic Wave Propagation Logs		
Full Waveform	X	X
Cement Bond Tool Log		X
Cement Evaluation Tool Log		X
Mechanical Logs		
Caliper	X	

Gamma spectrometry logging, which also detects naturally emitted radiation, differs from natural gamma logging in that it measures energy levels as opposed to total counts. In this manner, it is possible to differentiate between the source of the radiation (i.e., parent elements) due to their different characteristic spectra. It should be noted that these logs provide an indication of apparent fracture zones but that the status (i.e., open, infilled) of the fractures cannot be established without correlation with other logs.

Gamma-gamma density logging (or density logging) measures the bulk density of the formation as well as providing a measure of porosity when combined with information on the grain density and fluid density. In addition, lithologic changes and fracture zones are identifiable through inferences from logging response. The method is based on emitting gamma rays into the formation from the tool, monitoring the response in terms of loss of energy and evaluating the response based on documented responses for various rock types. The area of investigation is limited to the immediate area of the borehole with formation properties sometimes masked in larger and/or irregular boreholes (corrections are available for borehole diameter). The method is sensitive to naturally occurring gamma radiation and the logging equipment needs to be calibrated to minimize adverse impacts.

Neutron logs measure the attenuation of neutrons during travel through the near-borehole environment. As hydrogen atoms are most nearly equal in mass to the neutrons, the greatest attenuation of neutrons occurs in water. As a result, a low response on neutron logs is indicative of fracture zones and provides a measure of formation porosity. However, the response from these logs varies with rock type and the observed response (usually reported as apparent porosity) must be corrected by calibration with the rock type. Inferences can also be made with respect to water quality by comparing neutron and resistivity logs. Neutron logs may also detect zones of secondary mineralization, particularly along fractures, where the secondary deposits have a

higher hydrogen atom content than the surrounding media. Therefore, neutron logs may be misleading in attempting to identify fracture zones or formation porosity and need to be correlated with other logging results in order to be more conclusive.

The radius of measurement of neutron logging is a function of the density of the rock. In formations of higher porosity, neutrons are attenuated relatively close to the probe and the area of investigation is not great. This behavior also has a direct bearing on the borehole size relative to the probe size. In this regard, it is most desirable to use a probe which is not much smaller than the borehole diameter. Also changes in borehole diameter, due to erosion of the borehole wall, which adversely affect the logging response, may be corrected using a collimated or borehole compensated tool (ETC, 1985). Furthermore, the type of detector is also important in interpreting response. The most desirable detector is the compensated thermal-epithermal neutron detection tools with gamma and epithermal neutron detectors of lesser desirability (ETC, 1985).

Pulsed neutron logging (neutron activation and neutron lifetime) provides geochemical information on both the formation and the fluids by monitoring the response from a pulsed neutron (gamma) source. Also, information is provided regarding lithology and porosity. In particular, pulsed neutron logging is very sensitive to chlorides and provides a good indication of sodium chloride content of the formation.

It is recommended that the following radioactive logs be performed as part of the full scale field testing program:

- compensated neutron logging;
- natural gamma;
- gamma-gamma (density).

These logs are generally performed in conjunction with caliper logging.

In regards to the limited testing and monitoring programs, it is proposed that neutron logs be performed in the holes selected for use if these holes are presently cased (for uncased holes the logs proposed for the full-scale program should be considered). It may be possible that sufficient geophysical logs exist which are of a level of reliability which would make further logging redundant. In this case, it would not be necessary to perform these logs. However, for the purpose of deriving cost estimates, it is assumed that these logs will be performed (Table 3.6).

3.3.2.3 Elastic Wave Propagation Logging. Elastic wave propagation logging is based on the transmission of acoustic energy through geologic media. Acoustic wave propagation is related to a number of properties characteristic of the media through which it is being transmitted. These include, mineralogy, grain size and shape, pore volume and shape, clay content and distribution, rock mass fractures and formation permeability. Logging techniques falling into this category include conventional acoustic logging (also referred to as sonic or velocity logging) and full waveform logging, and interpretation techniques such as tube wave and acoustic televiewer logging.

Conventional acoustic logging measures only the travel time (velocity) of acoustic compressional wave propagation. The method involves transmitting an acoustic signal at a downhole transmitter and monitoring the travel time to reach a downhole receiver located at some distance away. The travel time is directly dependent on the condition of the geologic media, as the acoustic energy travels along the shortest pathway with respect to compressional velocity. Dense, unfractured media (i.e., intact rock) has a higher compressional velocity than fluids such that the waves are preferentially transmitted

through the rock. Anomalies in the rock (i.e., fractures, vugs, lithologic changes) affect the transit time and are evident in the signal received.

The acoustic wave velocities are directly related to and provide a measure of the rock density and elasticity. Velocities or transit times can be correlated with a number of engineering properties (i.e., bulk compressibility, shear modulus, Poisson's ratio) given that bulk density values are available (i.e., density logs) (ETC, 1985). Porosity is also measured by acoustic logging. Furthermore, acoustic logs run in fluid filled boreholes can be used to determine fracture occurrence, orientation and aperture (Paillet, 1980 in ETC, 1985).

A limitation of conventional acoustic logs (compressional waves) involves the inability to detect steeply dipping fractures. This limitation has been overcome by the use of full waveform logging; that is, the lower velocity shear and tube (Stoneley) waveforms are measured as well as the high velocity compressional waveform. Paillet (1983) reports that the most consistent indicators of open fractures are tube wave attenuation and distortion of shear wave arrival times. Furthermore, shear waves are useful in identifying lithology, porosity, rock elastic and inelastic properties and in shear seismics. Stoneley or tube waves correlate well with formation permeability and can be used as an indication of rock properties in unconsolidated soils where shear waves are often absent. In addition, tube waves are useful in that they not only serve in identifying fracture zones but are also capable of establishing whether a fracture is open or closed. Furthermore, tube waves have a much greater measurement volume than many downhole geophysical tests and are capable of sampling from 8 to 15 m radius around the borehole where fluid filled fractures exist. Also, fractures with apertures down to a small fraction of a millimetre are detectable (ETC, 1985).

A new sonic tool for full wave form logging has been developed by Schlumberger (undated). The tool differs from other sonic logging tools in that it has eight closely spaced, wideband range ceramic receivers in addition to the two receivers and transmitters in the sonic sonde. The waveforms are recorded and processed at the site using slowness time coherence to further enhance the rock properties derived from the test.

Tube waves have also been measured by Huang and Hunter (1984) using a somewhat different technique. Tube waves are measured using an array of 12 downhole hydrophones with the acoustic signal generated near the well head by a small detonation.

Schlumberger (undated) also reports that full waveform logs can be conducted in cased boreholes using a different data processing technique. As a consequence, this type of logging may be of great benefit in re-evaluating the geological and hydrogeological properties of existing cased boreholes. However, it should be noted that the reliability of these logs is directly related to the integrity (quality) of the cement job.

Acoustic televiewer logging is based on similar principles to conventional acoustic logging with the difference being the way data are recorded and presented. The reflectivity data from televiewer logs are transmitted to and displayed at surface and recorded using either a discrete photograph or a continuous analog signal. The method is good for fracture apertures greater than 1.0 mm in width (Lau et al., 1982 in ETC, 1985) and can be used to directly detect location of fracture zones in both cased and uncased holes but can only detect orientation in uncased holes. It should be noted that this method is useful in detecting steeply dipping fractures whereas conventional acoustic logs are not. Acoustic televiewer logs are also used to detect vugs and/or washouts, lithologic change, dip, porosity, size and shape of borehole and casing and formation damage.

Limitations of acoustic televiewer logs include the inability to detect closed or infilled fractures (unless there is a difference in acoustic reflectivity), the need for adjusting equipment in boreholes of variable diameter, the inability to detect fracture orientation (only) in cased boreholes, and the requirement for gas free liquid in the borehole.

The cement bond tool (CBT) is a modification of the more conventional cement bond log tool (CBL) which was designed to eliminate some of the deficiencies of the earlier version. According to Gollwitzer and Masson (1982), the CBT is "self-calibrating, and is not affected by mud attenuation, temperature effects, and eccentricity (up to 0.3 inches)". The tool has a number of transmitter/receiver separations which make it better able to characterize both fast and slow responses. The CBT yields a measurement of the compressive strength of the cement layer in the annulus and provides a qualitative estimate of the cement bond.

The cement evaluation tool (CEI) was initially designed to provide an assessment of the condition of the cement surrounding the casing. The method is based on the ultrasonic resonance of the casing and depends on the thickness of the casing, the medium behind the casing and is also sensitive to casing wear and corrosion (Dument et al., undated). The thickness of the casing is derived from the resonant frequencies of the pipe wall in conjunction with variations in internal diameter.

The CEI contains high ultrasonic transducers which allow a radial inspection of the casing and annulus. The response provides a qualitative measure of the integrity of the cement through its ability to detect unset slurry or liquid, gaseous cement, free gas and intact cement.

Of the elastic waveform logging techniques performed, full waveform logging is recommended over both conventional acoustic and acoustic televiewer logging for implementation in all alternative programs (i.e., cased and uncased boreholes). Although ultrasonic velocities and attenuation are known to be a function of a number of unknowns, the amount of information which is obtained from full waveform logging outweighs the limitations of the method. In particular, the high correlation of tube wave attenuation with permeability is considered to be of great use in planning a hydraulic testing program. Furthermore, the ability to determine whether fracture zones are infilled or open as well as the greater radius of measurement of full waveform logging is considered to be desirable.

In cased holes, it is desirable to perform both cement bond tool (CBT) and cement evaluation tool (CET) logging to provide an indication to the quality of cementing and the condition of the casing.

3.3.2.4 Mechanical Logging. The mechanical log of most relevance to the program is caliper logging. Caliper logs are useful in that they provide an indication of the condition of the borehole wall (i.e., diameter, deviations, erosion) as well as to identify discrete fractures and fracture zones. However, caliper logs are usually poor indicators of fracture aperture due to spalling during drilling/testing. The most desirable caliper log is a multi-armed log with up to four arms oriented in different directions. In order to optimize the fracture detection capabilities of caliper logs, it is essential to use small diameter arms adjusted for maximum sensitivity.

Caliper logs are generally run jointly with neutron and gamma logs and should be performed in any uncased boreholes used in the full scale or other monitoring programs.

A summary of all the recommended geophysical tests to be performed in cased (limited and monitoring only programs) and uncased (full scale program) are provided in Table 3.6.

3.3.3 Hydrogeochemical Sampling Program

As part of this feasibility study, it is necessary to design a hydrogeochemical sampling program to obtain background formation water samples and periodic monitoring well samples. The objective of the sampling program is to obtain representative formation fluid samples that are as free of contamination from drilling and sampling procedures as possible. It is recognized that any sampling procedure introduces some degree of contamination into the sample but with careful techniques contamination can be minimized. Much of what is described below is taken from a draft INTERA report entitled "Drill practices to improve quality of geochemical samples of formation fluids" by A. Haug (1985).

The context of this discussion is to design a field program suitable to collect representative formation fluid samples. Because there are a number of field program alternatives recommended in this study, a variety of sampling techniques are also suggested. These techniques depend on the borehole and sampling zone characteristics (diameter, casing interval, water yield), required reliability of the sample and the analytical purposes. The following discussion presents the variety of borehole conditions that may be found in the field, methods to increase the reliability of samples in newly drilled boreholes, (i.e., drill fluid tracers and borehole cleaning) and geochemical sampling equipment suitable for deep formations. Associated with the sampling technique will be a description of sample handling, preservation techniques, analytical protocols and quality control/quality assurance methods.

3.3.3.1 Borehole Conditions. The two borehole types that are of concern in this study are "old" and "new" boreholes. "Old" boreholes are those that were drilled for purposes other than hydrogeologic or hydrogeochemical investigations but may be suitable for geochemical sampling because of the installation of casing. The steel casing cemented into the borehole prevents cross-formational flow of groundwater and therefore when the casing is perforated may yield excellent samples from selected formations. Old boreholes however provide a large degree of uncertainty with regards to drilling procedures, well development and completion details as well as changes in water chemistry caused by cementing.

New boreholes, on the other hand, can be drilled specifically for hydrogeologic and geochemical purposes and therefore can be engineered to provide suitable groundwater samples. By using drilling and completion techniques that reduce or control the introduction of contamination into the borehole, representative groundwater samples can be collected.

Old boreholes are usually cased and must be perforated to provide sampling capabilities. New boreholes can be sampled during drilling, after drilling in the open borehole, through perforated steel casing or through multilevel casings. In both cases, the sampling method is dependent on a variety of borehole conditions. In deep boreholes, the depth to the sampling zone is a major factor in selecting a proper methodology. The hydraulic head and formation pressure in deep boreholes are high and therefore the methodology must be suitable to collect pressurized samples in these cases. The yield of the sampling zone is another important factor. In low yield zones, borehole flushing, pressure recovery and sampling volumes are limited resulting in special sampling techniques. Borehole or casing diameter, especially if less than 5 cm, can limit the sampling to small volumes or specially designed equipment. On the other hand, large diameter boreholes may prevent packer inflation and restrict sampling techniques

due to wash-out. Sampling methodology may also be restricted by the analytical purpose of the sample. For example, sampling for only major ions would typically require a much simpler technique than that required for formation gases, or trace organics.

In summary, the sampling methodology is largely determined by borehole conditions such as depth, head and yield of the sampling zone, borehole or casing diameter or analytical purpose.

3.3.3.2 Drilling Fluid Tracer Program. In many hydrochemical studies of deep formations, the presence of drilling fluids mixed with the natural waters have caused uncertainties in the interpretation of the background water quality. In order to reduce the uncertainty associated with groundwater sampling, it is recommended that tracers be added to the drilling fluid in all drilling programs. Tracers in the drilling fluid provide a measure of contamination introduced into the borehole during drilling. Background water quality samples are collected after all (or most of) the traced drilling fluid has been removed from the borehole.

According to Davis et al. (1980), an ideal groundwater tracer is "nontoxic, inexpensive, moves with the water, is easy to detect in trace amounts, does not alter the natural direction of the flow of water, is chemically stable for a desired length of time, is not present in large amounts in the water being studied and for most purposes is neither filtered nor sorbed by the solid medium through which the water moves". Obviously, a single tracer that possesses all these qualities is difficult, if not impossible, to find. Some tracers however have most of these attributes and can be used successfully as drill fluid tracers. More complete descriptions of tracer technology is given in Davis et al. (1980), Davis et al. (1985) and Grisak et al. (1983).

Three types of tracers are suggested for use as a drill fluid tracer: fluorescent dyes, inorganic ions and halogenated organics. Within these types are found tracers that possess most of the qualities listed above.

Fluorescent organic dyes have been widely used in groundwater applications with varying degrees of success. The stability of fluorescent dyes is often affected by temperature, salinity, and pH of the groundwater. Chemical and photochemical decay is also a problem with some dyes and most fluorescent dyes are at least weakly adsorbed by organic or inorganic solid phases. Table 3.7 from Grisak et al. (1983) summarizes the relevant characteristics of dyes according to experiments by Smart and Laidlaw (1977) and Gosphodaric and Habic (1976). With the restrictions noted in Table 3.7, it appears that Lissamine FF is the most suitable tracer although it does sorb weakly. Fluorescein and Rhodamine are also possibilities but Fluorescein sorbs moderately and decays quickly when exposed to light (Photochemical decay may be a problem through exposure in uncovered mud tanks). Rhodamine WT sorbs moderately and is particularly susceptible to temperature and salinity instabilities. Temperature gradients of 30°C/kilometre (ARC, 1985a) and salinity ranges from that of fresh water to the hundred thousand ppm range (ARC, 1985h) are known to occur in the study area possibly compromising the use of Rhodamine WT. Both Rhodamine WT and Lissamine FF are preferred over Fluorescein where mud is used as the drilling fluid because of Fluorescein's adsorption to clay particles. Lissamine FF is also relatively expensive compared to the other two and it also has a higher minimum detection limit. Fluorescent organic dye tracers have the advantage in that they can be measured in the field during drilling and sampling using relatively simple techniques. The concentration is determined by measuring the ultra-violet fluorescence in the visible range using a fluoro-colorimeter. These instruments are reliable and sturdy in a field situation.

Table 3.7 Characteristics of Fluorescent Dye Tracers (Grisak et al., 1983)

Dye	Minimum Detectability (ug/l)	Temperature Instability	Salinity Instability	Stable pH Range	Degree of Sorption	Photochemical Decay Rate
<u>Blue</u>						
Amino G acid	0.51	not significant	not significant	> 6.0	weak strong on organics	fast fast
Photine CU	0.36			> 6.5		
Tinopal CBS-X	0.011	?	?	?	moderate to strong	?
<u>Green-Yellow</u>						
Fluorescein	0.29 (0.005)*	not significant	not significant	> 6.5	moderate	fast slow fast
Lissamine FF	0.29	not significant	not significant	4.0 - 10.0	weak	
Pyranine	0.087	not significant	not significant	not strong in normal range of GW	weak	
<u>Orange-Red</u>						
Rhodamine B	0.010	significant	significant	> 5.0	strong	moderate-slow
Rhodamine WT	0.013	significant	significant (?)	4.0 - 10.0	moderate	slow
Sulphorhodamine B	0.061	significant	significant	> 5.0	weak	moderate-slow
Eosine	0.2 (0.05)*	?	?	moderately stable	weak	slow fast
Amidothodamine G	0.02 (0.005)*	?	?	stable	moderate	moderate

*Minimum detectability reported using improved spectrofluorimetric methods

Inorganic ions provide simple and inexpensive tracers for a variety of applications. Halide ions such as Cl^- , I^- , F^- and Br^- are all considered to be relatively non-reactive and have been widely used as tracers with Cl^- being the most popular. Cl^- and Br^- however may be found at high background concentration in deep sedimentary rocks of the study area (ARC, 1985a) and therefore would not be appropriate for a drilling water tracer. Fluoride is often restricted in its use because of precipitation controls due to the presence of calcium in groundwater. Iodide may be weakly adsorbed in some situations. Another anionic tracer is thiocyanate (SCN^-) which is commonly used in the petroleum industry. It is appropriate as a tracer because it is inexpensive and is easily detected in brine fluids. All of these ionic tracers can be detected using commercially available specific ion electrodes (Table 3.8 from Grisak et al., 1983). The electrodes estimate the ion concentration by measuring the activity of the uncomplexed ion in the aqueous solution. The method is simple and fast in a field situation and is only restricted by interference from other species. For this drill fluid tracer program, I^- or SCN^- are likely to be the most suitable ionic tracers for the drill fluid.

The third tracer type is an organic liquid developed especially for its tracer capabilities. The organic liquid is meta-trifluoromethylbenzoic acid (m-TFMBA) which is stable, inert, non-toxic at low concentrations and does not occur naturally in groundwater. M-TFMBA is detected to concentrations as low as 0.1 ppb using a high pressure liquid chromatograph (HPLC). The disadvantage of this technique is that it requires an expensive and technically difficult analytical instrument. M-TFMBA is an ideal drill fluid tracer but because of the expense and time associated with the analysis it is best used in conjunction with a more easily analyzed tracer.

Table 3.8 Characteristics of Selected Inorganic Ionic Tracers (Grisak et al., 1983)

Ion	Available Methods for field deter- minations (from: Hech; Orion; Thompson & Stetzenbach)	Limit of Detection (mg/L)	Concentration range (mg/L) in ground waters of the Canadian Shield (WNRE)	Comments
Na^+	electrode	0.02	8 - 1950	high natural concentration cation exchange
Ca^{++}	titrations (hardness as CaCO_3 electrode	0.4	17 - 1270	high natural concentration
		0.02		electrode interference cation exchange
K^+	electrode	0.4	1.2 - 12	electrode interference cation exchange
Cl^-	titration electrode	12.5 1.8	< 1 - 5410	high background concentration
Br^-	electrode chromatography	0.4 0.05	< 2.5	high sensitivity some sorption
I^-	electrode	0.005	< 0.12 - 0.24	high sensitivity low background concentration
F^-	electrode	0.02	0.6 - 4.1	high sensitivity some sorption at low pH
SCN^-	electrode chromatography	0.29 0.01	Not determined	high sensitivity

For the purposes of this drill fluid tracer program, it is recommended that one of the following dual tracers be used:

- Fluorescein, Lissamine FF or Rhodamine WT and M-TFMB;A;
- I^- or SCN^- and M-TFMB;A.

The purpose of using two tracers in the drilling fluid is to provide one tracer that can yield fast, inexpensive and moderately reliable results while the other tracer provides very reliable results at a more expensive and slower rate. The two types of tracers are mutually complementary and provide an effective method to trace the drilling fluid.

To implement a drill fluid tracer program, it is necessary to add the tracer to the drilling fluid, to ensure that the concentration of the tracer is maintained throughout the drilling program and to confirm the tracer concentration by frequent monitoring of the fluid.

The tracer can be added to the drilling fluid supply (i.e., fresh water. Note that samples of the water supply should be collected and retained for analysis) prior to mixing with mud by any suitable method that ensures complete mixing and a constant concentration. Reasonable tracer concentrations for the above listed tracers are as follows:

- Fluorescein, Lissamine FF or Rhodamine WT - 1 to 10 ppm;
- I^- or SCN^- - 10 to 30 ppm;
- M-TFMB;A - 1 to 10 ppm.

If the drilling fluid is replaced or if additional volume is required, it is important that the tracer concentration in the fluid remain relatively constant. During drilling, frequent monitoring (i.e., sample collection every two hours for example) of the drilling fluid is required to determine the tracer concentration and to ensure

that the tracer concentration remains constant. Tracer samples should be analyzed in the field on a regular basis (i.e., two per day, for example, for standard drilling and more frequently for changes in the drilling fluid volume).

During geochemical sampling, the tracer concentration can be used to determine the presence of drilling fluid and the need for borehole purging. Prior to the start of sampling, a reference sample of the borehole or interval fluid is taken. The tracer concentration in the sample is indicative of 100% contamination and borehole purging should continue until the tracer is not detected or until the tracer is found in only small concentrations. However, this can be complicated by interborehole flows from high to low head zones in the same boreholes. Careful monitoring of the tracer during purging will provide an indication of the effectiveness of borehole cleaning. Once the tracer concentration is negligible, it can be assumed that the borehole or interval is yielding representative formation water and sampling can begin.

3.3.3.3 Sampling Methods. In deep drilling programs, there are a variety of methods suitable for collecting representative groundwater samples. These methods vary from simple bailing techniques to sophisticated downhole geochemical probes and consequently provide samples with varying degrees of reliability. The type of sampling method is often dictated by the borehole conditions and analytical purpose as described previously. The following sampling techniques are described in order to provide an understanding of a number of sampling methods and the advantages and disadvantages of each:

- Bailing;
- Swabbing;
- Pumping;
- Sample vessels;
- Downhole geochemical probes.

(1) Bailing

Bailing of a well or test interval is perhaps the simplest technique for removing water. A bailer consists of an open cylinder of diameter and length sufficient to fit into the borehole, tubing string or casing with a one-way valve at one or both ends. The bailer is lowered into the well using a wire rope and winch. As it is lowered, water flows through the cylinder. When the bailer is removed, the valves close isolating the cylinder. Bailing has a number of advantages in that it is simple, suitable for any diameter and depth of borehole or casing and capable of collecting large volumes of water (depending on diameter and length of the bailer). Its main disadvantage is that a bailer does not provide an air tight sample. As the bailer is brought to the surface, the water depressurizes through the one-way valves resulting in a loss of formation gases or volatile contaminants. Similarly, the bailed sample must be transferred to another container (i.e., plastic or glass sample bottle) resulting in additional loss of formation gases. It is also possible that the valves do not completely close as the bailer is brought to surface and therefore it is uncertain that the water in the bailer is from the maximum depth or from elsewhere in the borehole. This problem is not important when the entire well or casing volume has been removed but often bailers are used to sample the lower portion of a borehole while the upper portion may still contain drilling fluid. A further limitation of the bailer is in deep boreholes where the depth to water is significant. In these instances, bailers are very time consuming and not the most practical means for sampling or purging wells.

(2) Swabbing

The most suitable method of removing large volumes of water from a drill casing or tubing string is by swabbing. A swabbing tool (Figure 3.7) consists of rubber sealing rings of same diameter as the casing at the bottom of a steel rod. The bottom of the rod contains a

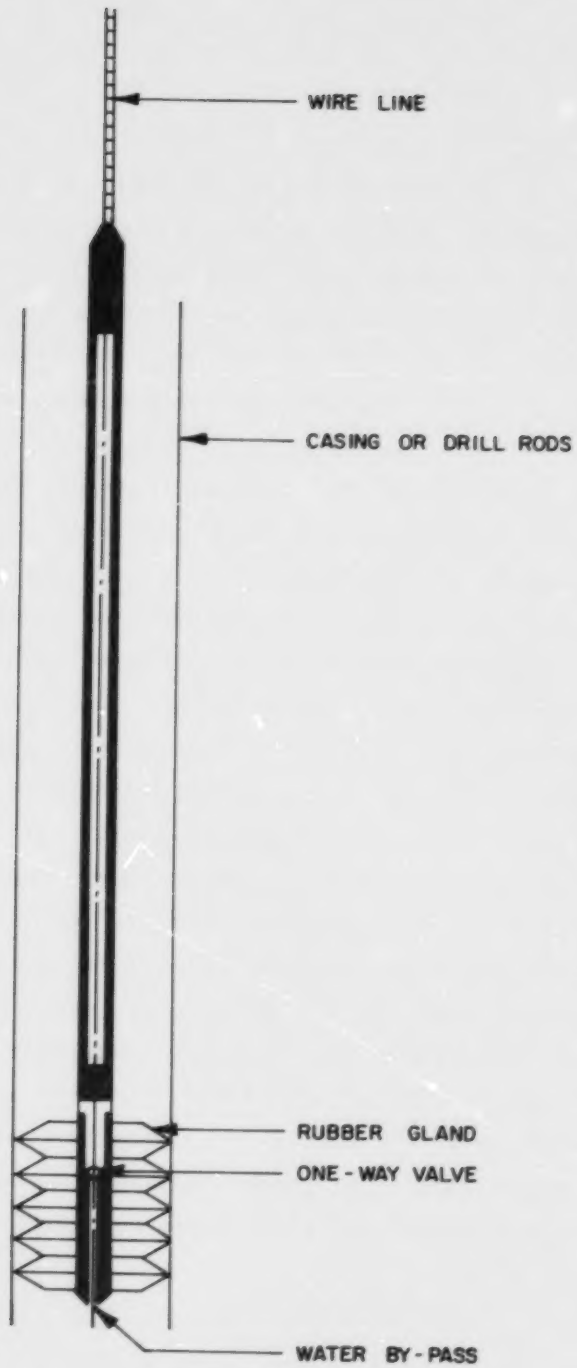


FIGURE 3-7 SWABBING TOOL

one-way valve to allow flow around the rubber seals as it is lowered into the borehole. The swabbing tool is lowered and raised via a wire line and winch on a work-over rig. When the tool is brought to surface, the valve closes and the rubber seals lift the water above the seals to surface where it is discharged at the well head. A swabbing head on the well is used to direct the flow of water and to collect samples in plastic or glass sample bottles.

Swabbing is a very effective and fast method of removing large volumes of fluid, especially drilling mud fluids, from the borehole. Swabbing is most effective at shallow depths. In deep boreholes with deep water levels, swabbing is somewhat less effective due to leakage around the seals caused by the suction pressure of raising the tool. However, the amount of leakage is a function of the condition of the well casing. Like bailing, swabbed samples are in contact with the atmosphere and therefore degas with a change in pressure. Swabbed samples would not be suitable for collecting samples to be analyzed for formation gases or volatile contaminants. During swabbing, the rubber seals are abraded along the casing which may cause rubber particles and casing rust to be found in the fluid samples.

Swabbing on its own is an effective method of purging water from the borehole and for sample collection for gross water quality but in general is unsuitable for detailed water quality studies.

(3) Pumping

A variety of submersible pumps are suitable for removing water from a borehole but their use is largely governed by the diameter of the borehole or casing and the maximum pump lift. Several types of submersible pumps are commercially available. The most common type of submersible pump consists of an electric motor that drives a series of impellers or turbines. The centrifugal force of the water within the spinning impellers lifts the water to surface. This type of pump can

be installed in boreholes or casings greater than 7.5 cm in diameter and are capable of producing up to 4000 L/min for a maximum lift of up to 300 m depending on the size and horsepower of the electric motor. Greater lifts can be achieved by "stacking" pump components in stages.

For smaller diameter boreholes or casings, submersible pumps are generally of a different type and produce at a much lower rate. There are submersible electrical/centrifugal pumps available (i.e., Keck Pump) that are less than 5 cm diameter but the maximum lift is limited to about 50 m. Greater lifts can be achieved by "stacking" additional pumps but it is not known whether the pump housing can withstand water pressures greater than 50 m. However, submersible impeller pumps do come in contact with the borehole fluids to be sampled.

Other small diameter submersible pump types are gas-driven piston pumps and gas-squeeze pumps. Gas-driven piston pumps use compressed air to move a piston up and down in an inner gas chamber. With each piston stroke, water is forced to surface from a water chamber (single-acting piston) or alternately from one water chamber while another chamber is filling (double-acting piston). One example of this pump is marketed by the Robert Bennett Company and is reported to produce up to 0.8 GPM with pump lifts of 1000 feet (Bennett, 1986).

The other submersible pump, a gas-squeeze pump, consists of a rubber, silicon or teflon bladder inside a pump chamber. When submersed, water fills the bladder through a foot valve at its base. Alternately, compressed air is applied to and released from the pump chamber squeezing and releasing the bladder. With each cycle, water is forced through an upper pump valve to surface. Several versions of this pump with pump rates up to 4 L/min are available commercially and one is made entirely of teflon. The maximum lift of this pump is largely dependent on the maximum differential pressure that the bladder and pump chamber can withstand.

All of these small diameter pumps are primarily for sampling purposes and are unsuitable for removing large volumes of water from the well bore. All of the submersible pumps are suitable for pumping clean water only and fluids containing drilling mud can severely damage the pumps.

In general, there are few disadvantages to the use of pumps in the sampling process. Pumps will provide sample collection at surface and with this process there will be a certain amount of degassing of the water. With an appropriate sampling head at surface, gas tight samples can be collected although the samples will not be at formation pressures. Samples collected at surface are typically pumped into plastic or glass containers. The only possible restrictions to pump usage during sampling may result from small casing diameters, low pump discharge rates or exceeding the maximum lift depth.

(4) Sample Vessels

Sample vessels can be used to collect downhole samples under a variety of conditions. A sample vessel is a simple stainless steel or stainless steel and teflon-lined chamber that is lowered into the borehole and filled with water then removed. In its simplest form, it is similar to a bailer but with electrically or pneumatically activated valves.

One type of sample vessel consists of a chamber that is evacuated on surface and sealed by an electrical valve. The vessel is then lowered by a wire line to the required depth. When the valve is opened the chamber fills with water, the valve is closed and the sample is brought to surface. This sample vessel provides a pressurized sample. The disadvantages of this type of sample vessel is that some degassing due to the change in pressure occurs when the valve is opened. If the sample has to be transferred from the vessel to another container prior to analysis, the degassed portion of the sample may be

lost. This sample vessel is usually of limited volume (i.e., approximately 2 litres) and if large sample volumes are required, this procedure can be quite time consuming.

INTERA staff have developed a sample vessel system to obtain water samples in small diameter wells and casings without degassing and to avoid atmospheric contamination. The INTERA-sampler (Figure 3.8) consists of a number of connected sample vessels with a ball valve at each end of each vessel. A water filter and a one way valve is connected to the lower end of the sample string. To the upper end of the sample string is connected a nylon tube and a wire strain member of sufficient length to reach the deepest test interval. To collect a sample, the tubing and sampling string is pressurized at surface to close the one way valve. The sample string is lowered to the required depth and the pressure is released. This causes the one-way valve to open and the sample vessels and tubing to fill with water. An over pressure is again applied to the tubing and sample string closing the one-way valve and sealing all the sample vessels. When the sample string is brought to surface the ball valves at each end of the sample vessels are closed and the vessels can be disconnected thus providing a pressurized sample.

This sampling methodology has the advantage in that it provides a sample at close-to-formation pressure without degassing. The system also provides for flushing of the sample vessels and no pressure release on the sample at the time of filling. The INTERA-sampler can accept any finite number of connected sample vessels including copper tubing for analysis of major and noble gases. This method allows for a large volume of sample in a number of different containers. The sample vessels also have the advantage of being transportable to the laboratory and of connecting directly to the analytical instrument to prevent atmospheric contamination or loss of sample due to volatilization.

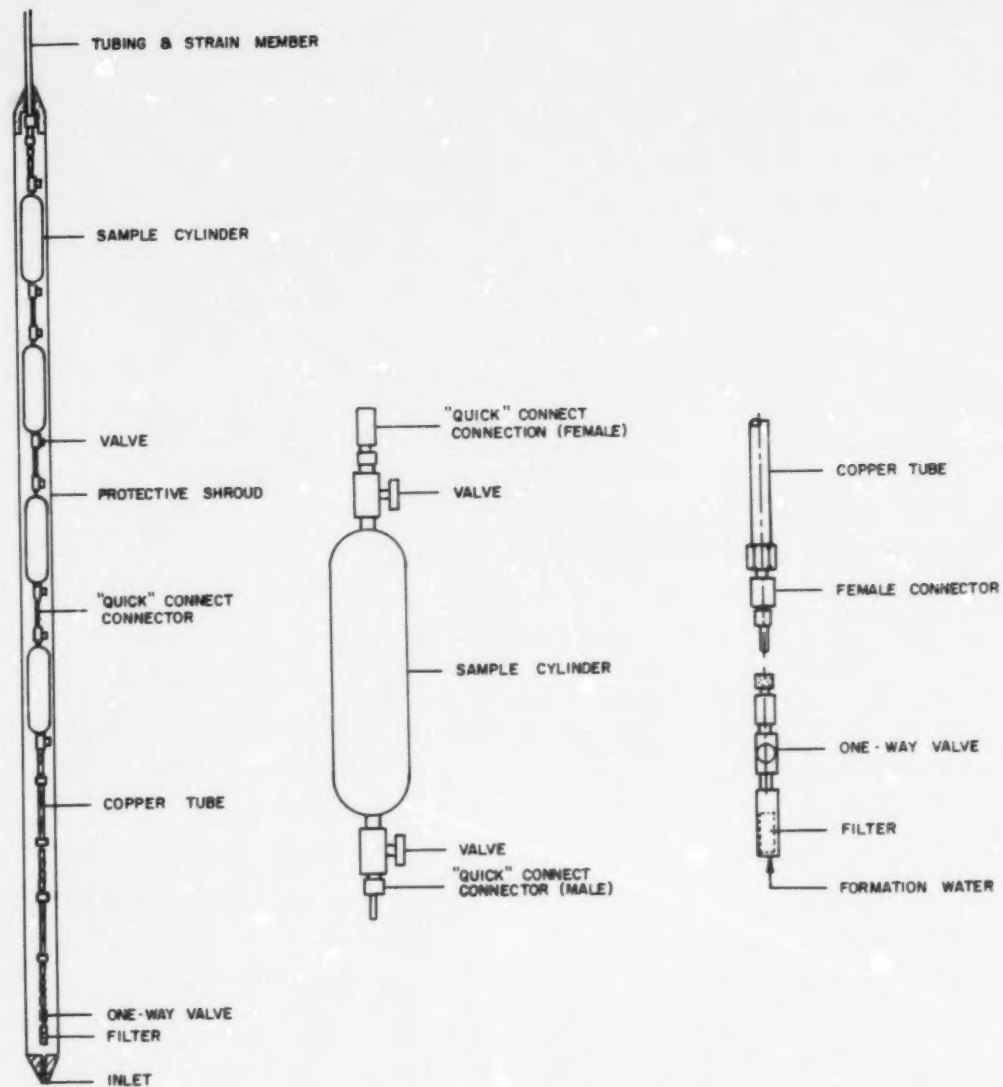


FIGURE 3-8 INTERA-SAMPLER (SCHEMATIC)

Other sample vessels have been used in association with hydraulic testing equipment or multipacker casings. For example, Lynes Drill Stem Test Tool has the capability of filling a sample vessel at the end of a hydraulic test. This sampler is pressurized and will hold two litres. Another example is the sample vessels associated with Westbay Instruments packer casing system. This device uses an evacuated cylinder that is electronically controlled. It attaches to a pressure port to sample outside the casing and is filled by opening the valve. The disadvantage of this sample vessel is that it does not allow for flushing of casing water prior to sampling.

(5) Downhole Geochemical Probes

The most advanced method of collecting downhole geochemical measurements and groundwater samples is by using a specially designed geochemical probe. Probes such as this have been used by Environment Canada in Atomic Energy of Canada Limited's Waste Management Program to sample deep groundwaters in crystalline rock. The probe, as designed by Bottomley et al. (1984) (Figure 3.9) consists of two inflatable packers, a downhole pump, in line geochemical probes, a series of sample cylinders, and an umbilical cable and cable reel. The packers are used to isolate a section of borehole or casing for testing. The downhole pump is a double-acting piston pump (R. Bennett Co.) that is used to draw test section water past the geochemical probes, through the sample cylinders and then to surface. The downhole geochemical probes consist of pH, temperature, electrical conductivity, redox, pressure and dissolved oxygen sensors. Sample cylinders are used to collect downhole samples. The umbilical cable provides the tubing and electrical connections to surface to operate the probe. The entire probe is moved within the borehole using a cable reel and winch system.

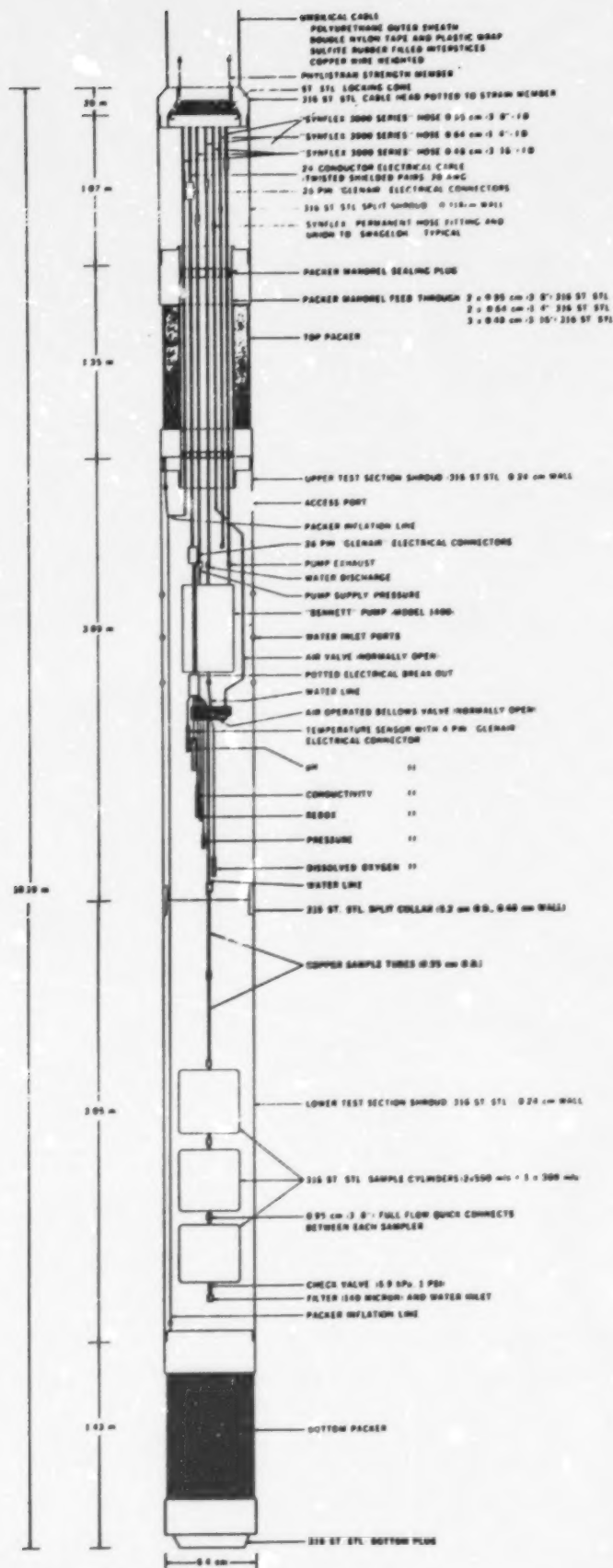


Figure 3.2 Borehole Hydrogeomechanical Probe (Bottonley et al., 1984)

To use the probe, it is lowered via the cable reel to the required depth in the open borehole or casing (7.6 cm minimum diameter). Once at the required depth, the packers are inflated to isolate the interval and the pump is started. The pump draws formation water into a shroud where it circulates past the geochemical probes. The probes are connected electrically to surface where they provide continuous sensor readings. The inlet for the pump is at the base of a number of stainless steel and copper tubing sample vessels and all water pumped to surface first passes through the sample vessels. Test water is pumped to surface through the umbilical cable where additional geochemical measurements and groundwater samples are collected. Downhole and surface geochemical measurements are used to indicate if formation waters or drilling fluids are being sampled. Once it is determined that formation waters are in the test interval, the pump is stopped and the sample vessels are sealed downhole by a pneumatic valve. In this manner, the sample vessels contain the last water brought into the interval.

The advantages of the downhole geochemical probe are as follows:

- Provides downhole geochemical measurements at in situ conditions;
- Collects downhole samples at in situ conditions as well as samples at surface;
- Suitable for sampling in stable, open boreholes or inside cased boreholes of diameter greater than 7.6 cm.

Unfortunately, there are a number of disadvantages also associated with this equipment as follows:

- The system is expensive to design, construct and operate;
- The present state of downhole sensors is such that the reliability of some sensors is questionable over long sampling periods due to sensor drift, electrode poisoning, or electrical problems;
- Because of its complexity the geochemical probe often experiences operation problems that reduce its effectiveness.

The biggest disadvantage is the great expense of developing the system. Although most of the components are commercially available, the entire system must be constructed by the user. With the high complexity of the system, a significant amount of development time must be spent prior to actually collecting samples.

3.3.3.4 Sampling Protocols. In the design of a sampling program, it is necessary to develop protocols that guide the sampling procedures in terms of the following considerations:

- Sampling materials;
- Equipment cleaning;
- Special sampling considerations for organic samples;
- Sample preservation techniques;
- Sample control and handling.

This section provides a brief discussion on each of these topics and recommends procedures to enhance the integrity of the sampling program and analytical results.

(1) Sampling Materials

The primary requirements for sampling materials and equipment are that they be non-contaminating and non-adsorbing. The preferred materials with these characteristics are glass, teflon and stainless steel but glass is too fragile to use in a borehole sampling procedure and all-teflon equipment is prohibitively expensive. The most common material for deep sampling methods is stainless steel and in some cases teflon-lined stainless steel (i.e., sample vessels). Wherever possible the material in contact with the sampling water should be stainless steel or teflon. In many cases, however, it is impossible to limit the sampling equipment to non-contaminating materials. Sampling equipment such as swabbing tools, packers, and valves often contain rubber or plastic components which are prone to leaching or adsorption of some parameters (i.e., organic contaminants). Drill casings are often in contact with the water to be sampled and are unavoidably made of carbon steel. Lubricants or moving parts of the sampling equipment or on threaded joints are another possible source of contamination in the sampling equipment. Although it is often impossible to eliminate all these sources of chemical interference in the sampling procedure, recognition of possible sources and reducing contact or eliminating their use will increase the reliability of the sampling procedure.

(2) Equipment Cleaning

All equipment in the drilling, testing and sampling procedure require cleaning prior to use to prevent the introduction of contaminants into the formation fluids. Equipment cleaning is considered of primary importance in a drilling, testing and sampling program where samples are to be collected for organic contaminants. In most hydrogeologic deep formation studies, the natural groundwaters may come in contact with drilling equipment, drilling fluids, hydraulic testing equipment, swabbing tools, pumps and sampling equipment in the borehole and if all equipment is not cleaned to a common standard it

becomes difficult to interpret trace levels of natural constituents or contaminants. The following comments provide guidelines for equipment cleaning.

Drilling equipment such as drill bits, rods, or casing should be washed with detergent and steam cleaned prior to use (Note: samples of wash water should be collected and retained for analysis). Special care should be taken to remove as much grease and lubricants from this equipment as possible. The use of lubricants on downhole drilling equipment should be avoided if possible. If necessary, teflon or silicon based lubricants may be used. After cleaning, it is often useful to quantify the effectiveness of the cleaning process and to identify equipment related contaminants by running deionized water through selected pieces of equipment and retaining the sample for complete analysis of all required parameters. Clean equipment should be stored away from possible sources of contaminants.

Hydraulic testing equipment should undergo cleaning similar to the drilling equipment. Each time this equipment is removed from the borehole, it should be recleaned in a similar manner.

Sampling equipment such as swabbing tools, bailers, pumps, sample vessels, sample bottles and related pieces requires more diligent cleaning than other equipment. Detergent and steam cleaning is recommended as the first step in the process. In addition, thorough rinsing with high purity deionized water is required to reduce contamination caused by the cleaning water. For organic analyses, sample containers should also be washed with acetone and heated to 295°C for two hours. All sampling equipment should be recleaned between sampling events.

(3) Sample Control and Handling

Proper sample control and handling procedures are required to ensure the identification of each sample and the validity of the analytical results. An outline of these procedures, given in Table 3.9 essentially consists of sample labelling, identification and chain of custody.

The procedure begins after the sample containers (plastic or glass bottles and/or sample vessels) have been cleaned and securely capped. For each sample container the cleaning technique used should be identified. As a minimum requirement, whole boxes of similarly cleaned containers can be labelled.

After the sample has been collected the sample container must be identified in an appropriate manner including the following information (Table 3.10):

- Date and time of sampling;
- Sample number and/or identification number (laboratory assigns the sample a lab number);
- Well number and interval depth;
- Sample type (i.e., inorganic/organic, isotope, pressurized sample);
- Sampling method (i.e., swab, pump or pressurized vessel sample);
- Preservation technique (if any);
- Sampler's signature.

All labels must be securely attached to the sample container or must be marked in indelible ink directly onto the container.

Table 3.9 Sample Control and Handling Procedures

-
- (1) Sample container/vessel cleaning and storage of clean capped containers;
 - (2) Sample collection;
 - (3) Sample Numbering and Labelling (Form 1, Table 3.10);
 - (4) Sample Record Log (Form 2, Table 3.11);
 - (5) Chain of Custody Record (Form 3, Table 3.12);
 - (6) Refrigeration Unit Storage Record;
 - (7) Laboratory numbering and analysis.
-

Table 3.10 Sample Identification and Labelling

Date: _____	Time: _____
Sample Number: _____	Laboratory Number: _____
Well Number: _____	Depth Interval: _____
Sample Type: _____	
Sample Method: _____	
Preservation Technique: _____	
Type of Analysis Required: _____	
Sampler Signature: _____	

The sampling details should also be recorded onto a sample record log (Table 3.11). This log provides all the necessary details to describe the sample, the sampling methodology, on-site geochemical analysis and other information important to the interpretation of the results. The sample record log forms the detailed description of the sample. Typically, one copy of this log accompanies the sample and another forms the official record of the sample.

The chain of custody record (Table 3.12) is required to define the responsibility of custody and the final disposition of the sample. It is of particular importance in sampling associated with legal action. Each time the sample is transferred a record of possession must be maintained. The following comments regarding chain of custody from USEPA (1977) form a basic guideline:

- As few people as possible should handle the sample;
- Samples should be collected by standard field methods;
- The chain of custody record (i.e., Table 3.12) should be attached to the sample container at the time the sample is collected;
- Custody transfers should be recorded for each individual sample;
- Blank samples should be collected in containers with and without preservatives, so that the laboratory analysis can be performed to show that there was no container contamination;
- A field book or log (i.e., Table 3.11) should be used to record field measurements and other pertinent information;
- The field sampler is responsible for the care and custody of the samples collected until properly dispatched to the receiving laboratory or turned over to an assigned custodian;

Table 3.11 Sample Record Log

Sample number: _____		Laboratory number: _____		Well number: _____		Date: _____		Time: _____	
Sample type: _____		Sampling method: _____		Depth interval: _____					
Preservation technique: NaOH _____, Cool, 4°C _____		Acidification (specify) _____		Other _____					
Type of analysis required: _____									
Sample description: _____		Sample volume: _____							
Field analytical results: pH _____		Eh _____		Electrical conductance _____					
Temperature _____		Dissolved oxygen _____		Drill tracer _____					
Container type: _____		Cleaning method: _____							
Type of well: _____		Depth to water: _____							
Purpose of sample: _____									
Weather conditions: _____									
Sampler signature: _____		Affiliation: _____							
Storage location: _____		Type of storage: _____							
Designated laboratory: _____									
Comments: _____									

Table 3.12 Chain of Custody Record

Date: _____ Time: _____
 Sample Number: _____ Laboratory Number: _____
 Well Number: _____ Depth Interval: _____
 Sample Type: _____
 Sample Method: _____
 Preservation Technique: _____

Custody of Samples

	Name	Affiliation	Date	Time
1) Sample container Prepared by	_____	_____	_____	_____
2) Received by	_____	_____	_____	_____
3) Received by	_____	_____	_____	_____
4) Sample collected by	_____	_____	_____	_____
5) Sample received by	_____	_____	_____	_____
6) Sample received by	_____	_____	_____	_____
7) Sample received by	_____	_____	_____	_____
8) Sample received by	_____	_____	_____	_____
9) Sample received at Lab. by	_____	_____	_____	_____

Note: During transport of the sample from sampling site to laboratory, the chain of custody must be unbroken. This chain requires that the sample be delivered by the sample collector or his designated representative who will sign for the receipt, integrity and transfer of the sample during shipment.

- Each laboratory should have a sample custodian to maintain a permanent log book in which he records for each sample the person delivering the sample, the person receiving the sample, date and time received, source of sample, sample number, how transmitted to the laboratory, and a number assigned to each sample by the laboratory.

(4) Special Considerations for Organic Samples

In the hydrogeochemical program, it is necessary to review the special considerations that are required for the sampling of organic contaminants. Presently, there are a number of methods suitable for collecting organic samples in groundwater but most techniques are relatively new and have been used mostly in research applications. These methods have been developed for use in sampling shallow groundwaters and their success in deep formations has not been documented. However, the methods and techniques are fundamentally simple and should lend themselves to adequately sampling deep groundwater. The primary considerations of organic sampling are to reduce potential contamination and to eliminate sample loss by volatilization or adsorption during the sampling process.

Sampling for organic parameters requires scrupulously clean equipment and non-contaminating and non-adsorbing materials. It may be difficult to meet these requirements in a deep drilling program where drilling equipment is associated with the sampling process. Sampling equipment and containers made of glass or teflon are preferred materials however stainless steel may be used successfully. Surface sample containers should be made of glass with teflon liners. Sample pumps such as an all-teflon gas-squeeze pump provide a non-contaminating method to sample deep formation waters. For use in the INTERA-sampler, teflon sample vessels and valves are commercially available.

All sampling equipment (i.e., sample vessels, tubing, etc.) that is in direct contact with the sample water should be initially cleaned with detergents and rinsed extensively with tap water. Final rinsing successively with high purity deionized water, acetone and hexane and then heating to 295°C for two hours is also required.

There are presently two types of techniques suitable for collecting organic samples without a loss of volatile components: closed sampling methods and adsorbent columns.

Closed sampling methods ensure that the sample water does not contact the atmosphere whereby it could lose volatile components. Sampling methods such as the INTERA-Sampler or other downhole pressurized sampling techniques are examples providing they do not have to be transferred to another container for analysis. Most sample vessels can be adapted to discharge directly to the analytical instrument (i.e., GC/MS) thereby preventing any loss of sample. Downhole pumping techniques can also result in closed samples by the use of a sampling head at the surface well head. The sampling head consists of ports to which sample containers can be attached. The sample containers are evacuated of air and sealed by a teflon valve then attached to the port of the sample head. When the valve is opened, the sample container is filled. By closing the valve, the sample is contained without contact to the atmosphere. A similar technique, developed by Jackson et al. (1985), prevents the depressurization of the sample caused by the vacuum by using a glass syringe with a teflon plunger. In this method, the syringe, equipped with a teflon valve, is attached to the sampling port. The valve is opened and the force of the pumped water depresses the plunger thus filling the syringe. When the valve is closed the syringe can be detached from the sampling head and transported to the laboratory. The syringe has the advantage in that it can be used to inject directly into the analytical instrument while in the other methods the water sample would have to be displaced by an inert gas.

Adsorbent columns are used to concentrate and recover organic constituents by passing the groundwater through an adsorbing material. The adsorbing materials are typically macroreticular resins, activated carbon or polyamide particles. The procedure consists of filling a column with the adsorbing materials then passing the groundwater through the column, either downhole or at surface. The adsorbing material collects the organic components from the ground water. The more groundwater that passes through the column, the more organics are collected in the column, and the more sensitive the analysis. After a known volume of groundwater has passed the column, the column is removed and immediately sealed for transportation and analysis. The organic material is eluted from the column and analyzed by standard methods (i.e., GC/MS). Depending on the volume of water flowing through the column, this method can detect organic parameters to about one part per billion.

Although this method has not been conducted in deep groundwaters (i.e., depths greater than 100 m) the procedure should be effective. Adsorbent columns could be included in a sample vessel string such as the INTERA-Sampler or could be attached, downhole, to a sampling pump but the easiest method would be to pass water through the column at surface using a downhole pump. A downhole method has been used by Pankow et al. (1984) to sample shallow groundwater that may be applicable to deep sample systems. The method consists of attaching the column to a syringe. The syringe is adapted such that the plunger end of the syringe is attached to an air tube and the plunger can be activated by air pressure at ground surface. The sampling device is lowered downhole with pressure applied to the air tube to keep the plunger in the down position. Once at the required depth the pressure is released and a vacuum applied to bring the plunger into the up position whereby a measured volume of groundwater has passed the column. The device can be removed and the column used to analyze the adsorbed organics.

(5) Preservation Techniques

Preservation techniques for groundwater samples are well established and recommended procedures for preservation, appropriate sample containers and recommended holding times are given in Table 3.13. Although these are recommended methods, it is best to co-ordinate the sampling procedure with the laboratory responsible for analysis to ensure that the preservation technique is suitable for the analytical purpose intended. Some laboratories prefer filtered samples for special analyses (i.e., metals) while others do not. It is also important to ensure that the laboratory is able to perform the analysis within the required holding time.

3.3.3.5 Analytical Protocols. The analytical protocols described in this section are, for the most part, well established for the parameters in question. They have been drawn from such publications as: Standard Methods for the Examination of Water and Wastewater (APHA, AWWA, WPCF, 16th Edition, 1985); "Analytical Methods Manual" (Environment Canada, 1979, 1981), "Annual Book of ASTM Standards - Water" (1979); and Methods for Chemical Analysis of Water and Wastes, (USEPA, 1979). Each of these references provide step-by-step procedures for each method and therefore only brief descriptions will be provided here.

A list of inorganic and organic contaminants to be quantified in the sampled waters is given in Table 3.14. This table is too extensive for routine monitoring in most cases and therefore screening of samples may be required initially to determine gross water quality. For organic contaminants, screening tests such as total aromatic hydrocarbons, total chromatographable organics, total organic carbon, total volatile organics and total phenolics can be used to provide a qualitative and less expensive scan of water quality in a monitoring program. The screening tests can be followed by more detailed and quantitative analyses for indicator parameters or full suite analyses (i.e., Table 3.14) if a degradation in water quality is noted. The

Table 3.13 Recommended Preservation Techniques, Sample Container and Holding Times

Measurement	Vol. req. (ml)	Container	Preservation	Holding time ¹	Standard Method Number ²
Acidity	100	P, G ^a	Cool, 4°C	24 hrs	402
Alkalinity	100	P, G	Cool, 4°C	24 hrs	403
Arsenic	100	P, G	HNO ₃ to pH < 2	6 mos	404
BOD	1,000	P, G	Cool, 4°C	6 hrs ^c	507
Bromide	100	P, G	Cool, 4°C	24 hrs	406
COD	50	P, G	H ₂ SO ₄ to pH < 2	7 days	508
Chloride	50	P, G	None Req.	7 days	408
Chlorine Res.	50	P, G	Cool, 4°C	24 hrs	412
Color	50	P, G	Cool, 4°C	24 hrs	204
Cyanides	500	P, G	Cool, 4°C	24 hrs	413
Dissolved Oxygen			NaOH to pH 12		
Probe					402
Wincler	300	G only	Det. on site	None	
Fluoride	300	G only	Fix. on site	None	
Hardness	100	P, G	Cool, 4°C	7 days	414
Iodine	100	P, G	Cool, 4°C	7 days	309
MBAS	100	P, G	Cool, 4°C	24 hrs	416
Metals	250	P, G	Cool, 4°C	24 hrs	512
Dissolved	200	P, G			301
Suspended					
Total	100		Filter on site	6 months	
Mercury			HNO ₃ to pH < 2		
Dissolved	100	P, G	Filter on site	6 months	315
			HNO ₃ to pH < 2		
	100	P, G	Filter	38 days (glass)	
			HNO ₃ to pH < 2	13 days (hard plastic)	
				38 days (plastic)	
	100	P, G	HNO ₃ to pH < 2	13 days (glass)	
				13 days (hard plastic)	
Nitrogen					
Ammonia	400	P, G	Cool, 4°C	24 hrs ^d	417
			H ₂ SO ₄ to pH < 2		418
Kjeldahl	500	P, G	Cool, 4°C	24 hrs ^d	421
			H ₂ SO ₄ to pH < 2		
Nitrate	100	P, G	Cool, 4°C	24 hrs ^d	419
			H ₂ SO ₄ to pH < 2		
Nitrite	50	P, G	Cool, 4°C	24 hrs ^d	420
NTA	50	P, G	Cool, 4°C	24 hrs	—
Oil & Grease	1,000	G only	Cool, 4°C	24 hrs	502
			H ₂ SO ₄ to pH < 2		

Measurement	Vol. req. (ml)	Container	Preservation	Holding time ¹	Standard Method Number ²
Organic Carbon	25	P, G	Cool, 4°C	24 hrs	505
			H ₂ SO ₄ to pH < 2		
pH	25	P, G	Cool, 4°C	6 hrs ^c	424
Phenolics	500	G only	Det. on site		
			Cool, 4°C	24 hrs	574
			H ₂ PO ₄ to pH < 4		
			1.0 g CuSO ₄ /l.		
Phosphorus					
Ortho-phosphate, dissolved	50	P, G	Filter on site	24 hrs ^d	425
Hydrolyzable	50	P, G	Cool, 4°C	24 hrs ^d	
			Cool, 4°C		
			H ₂ SO ₄ to pH < 2		
Total	50	P, G	Cool, 4°C	24 hrs ^d	
Total, dissolved	50	P, G	Filter on site	24 hrs ^d	
Residue					
Filterable	100	P, G	Cool, 4°C	7 days	208
Non-filterable	100	P, G	Cool, 4°C	7 days	
Total	100	P, G	Cool, 4°C	7 days	
Volatile	100	P, G	Cool, 4°C	7 days	
Settleable					
matter	1,000	P, G	None Req.	24 hrs	208
Selenium	50	P, G	HNO ₃ to pH < 2	6 months	318
Silica	50	P only	Cool, 4°C	7 days	426
Specific					
conductance	100	P, G	Cool, 4°C	24 hrs ^e	205
Sulfate	50	P, G	Cool, 4°C	7 days	427
Sulfide	50	P, G	2 ml zinc acetate	24 hrs	428
Sulfite	50	P, G	Cool, 4°C	24 hrs	429
Temperature	1,000	P, G	Det. on site	None	212
Threshold					
odor	200	G only	Cool, 4°C	24 hrs	206
Turbidity	100	P, G	Cool, 4°C	7 days	214

^aMore specific instructions for preservation and sampling are found with each procedure as detailed in the literature. A general discussion on sampling water and industrial wastewater may be found in ASTM, Part 23, p. 72-91 (1973).

^bPlastic or glass.

^cIf samples cannot be returned to the laboratory in less than 6 hrs and holding time exceeds this limit, the final reported data should indicate the actual holding time.

^dMercuric chloride may be used as an alternate preservation at a concentration of 40 mg/l, especially if a longer holding time is required. However, the use of mercuric chloride is discouraged whenever possible.

^eIf the sample is stabilized by cooling, it should be warmed to 25°C for reading or temperature correction made and results reported at 25°C.

Table 3.14 List of Inorganic and Organic Contaminants to be Quantified in Injection Liquids Sampled (from Terms of Reference for this study)

<u>Inorganic</u>	<u>Organic</u>
Oil and Grease	Benzene
Total Dissolved Solids	Toluene
Total Suspended Solids	Xylene
Alkalinity	Alkyl Substituted Benzenes
Total Organic Carbon	Phenol
Total Hardness	Naphthalene
Nickel	Methylnaphthalene
Mercury	Biphenyl
Cadmium	Benzothiophene
Chromium	Dihydroacenaphthylene
Copper	Dibenzofuran
Iron	Fluorene
Lead	Benzo(ghi)fluoranthene
Manganese	Phenanthrene
Zinc	Anthracene
Aluminum	Chrysene
Calcium	Triphenylene
Magnesium	Pyrene
Potassium	Benzo(a)fluorene
Silica	Benzo(a)pyrene
Sodium	Benzo(b)thiophene
Nitrate	Dibenzothiophene
Sulphate	Dimethylantracene
Chloride	Methylfluorene
Bromide	Methylphenanthrene
Iodide	Trimethylphenanthrene
Nitrite	Tetramethylphenanthrene
Nitrogen-Kjeldahl	Benz(a)anthracene
	Methylbenz(a)anthracene
	Benzo(c)phenanthrene
	Methylbenzo(c)phenanthrene
	Methylchrysene
	Dimethylchrysene
	Fluoranthene
	Methylpyrene
	Benzo(c)chrysene
	Benzo(g)chrysene
	Methylbenzo(a)pyrene
	Dimethylbenzo(a)pyrene
	Benzo(e)pyrene
	Benzo(b)fluoranthene
	Benzo(j)fluoranthene
	Dibenz(a,c)anthracene
	Cholanthrene
	Perylene
	Auramine
	N-methyl-4-aminobenzene
	2,4-Diaminotoluene
	Pyridine
	Nitronaphthalene
	Naphthylamine
	Quinoline
	Dimethylbenzidine
	Methylquinoline
	Nitrofluorene
	Aminoacridine
	Aminofluorene
	Nitropyrene
	Benzo(a)carbazole
	Benzacridine
	Aminoperylene
	Benzoic Acid
	Dihydroxybiphenyl
	Dihydroxyphenol
	Methylindene
	Indene
	Acenaphthene
	Halogenated Phenolics
	Chlorobenzenes
	Dibutyl Phthalate
	Diethyl Phthalate
	Nitrobenzenes
	Nitrophenols

use of indicator parameters is recommended however the cost of identifying one parameter in a chemical group (i.e., naphthalene in polyaromatic hydrocarbons) is not substantially different from the cost associated with identifying the entire chemical group.

In choosing indicator parameters it is important to consider the behavior of the parameter in groundwater systems. Chemical properties such as aqueous solubility, volatilization, adsorption and biodegradation will govern the environmental fate of injected waste liquids. Indicator parameters which have high solubility, low volatility, low adsorption and low biodegradation will move at about the same velocity as the injected water and therefore will provide a good indication of the migration of the waste fluid.

The selection of indicator parameters from the list of organic contaminants given in Table 3.14 is limited to those parameters for which the chemical properties are well understood. In most cases simple compounds are better defined than more complex compounds. Suitable indicator parameters chosen because of their well understood chemical properties may include benzene, phenol, naphthalene, quinoline and methylaniline.

A summary of the detection limits for all required inorganic parameters as well as the corresponding methods are listed in Tables 3.15 and 3.16. Organic contaminants require more sophisticated methods and suggested methods are described.

(1) Analysis of Inorganic Parameters

The concentration of inorganic parameters in groundwater can be determined by a number of different methods. Two primary methods have been chosen; one for the determination of trace metals using Inductively Coupled Plasma (ICP) Atomic Emission Spectrometry; and the other for the determination of anions using Ion Chromatography. The ICP method is suitable for determining all the trace metals listed in

Table 3.15 Methods and Detection Limits for Chemical Analyses

Parameter	Det. Lim.	Waters	Methods
NH ₃	0.01 mg/L		Colourimetry
NO ₃	0.05 m/L		I.C.
Cl	0.05 mg/L		I.C.
SO ₄ ⁼	0.05 mg/L		I.C.
S ⁼	-		-
S	0.05 mg/L		(Oxidizable)
<u>Alkalinity:</u>			
OH ⁻ (as CaCO ₃)	0.2 mg/L		Titrimetry
CO ₃ ⁼ "	0.2 mg/L		Titrimetry
HCO ₃ ⁻ "	0.2 mg/L		Titrimetry
Total Solids	mg/L		Gravimetry
Total Dissolved Solids	2 mg/L		Gravimetry
pH	0.01 units		Meter
Ca	0.01 mg/L		I.C.P.
Mg	0.01 mg/L		I.C.P.
Mn	0.01 mg/L		I.C.P.
Ni	-		-
Oxygen	0.01 mg/L		Electrode
EH	mV		Electrode
Metal Scan	see Table 3.16 - I.C.A.P.		

Table 3.16 ICP Atomic Emission
(all values are in mg/l)

Matrix	Element	Detection Limit	Top of Range	Precision Between Run	Accuracy*
Preconcentrated Aqueous Digests	Al	.02	350	1.44 $\pm$.05	+0.01 @ .4
	As	.05	400		-.003 @ .06
	B	.005	180	1.56 $\pm$.05	
	Ba	.002	40	1.25 $\pm$.03	
	Be	.002	2	1.75 $\pm$.06	-0.1 @ .2
5% HNO ₃ Optimum Surface Water and Drinking Waters	Ca	.02	300	2.02 $\pm$.19	
	Cd	.002	30	1.80 $\pm$.04	-.002 @ .03
	Co	.005	70	1.79 $\pm$.05	-.003 @ .10
	Cr	.005	50	1.75 $\pm$.03	-.003 @ .06
	Cu	.005	50	1.63 $\pm$.02	+0.006 @ .05
	Fe	.008	150	1.74 $\pm$.04	-.003 @ .08
	Mg	.08	400	2.02 $\pm$.03	
	Mn	.002	17	1.81 $\pm$.04	+0.001 @ .05
	Mo	.005	40	1.65 $\pm$.03	
	Ni	.01	60	1.92 $\pm$.06	+0.003 @ .10
	P	.1	1300	1.10 $\pm$.08	
	Pb	.05	300	1.73 $\pm$.05	-.003 @ .11
	S	.1	120		
	Se	.1	400		+0.001 @ .02
	Sn	.1	400		
	Sr	.005	30	1.27 $\pm$.01	
	Ti	.005	25	4.58 $\pm$.06	
	V	.005	50	1.31 $\pm$.04	-.02 @ .5
	Zn	.002	40	1.72 $\pm$.05	-.003 @ .03

Table 3.16. The method requires samples free of organics and suitable for aspiration into a plasma discharge. The plasma serves as an atomization device and as a source of excitation energy. Each metal atom emits its own radiation and the energy of this radiation, as detected by a spectrometer, is indicative of the metal present. The concentration of the metal is measured by the intensity of the energy. In groundwaters, this method is usually accurate to about 0.01 mg/L at detection limits of 0.1 mg/L. Interference problems occur only when high concentrations of one element is found in the presence of another at low concentration.

The Ion Chromatography method can be used to identify anions such as Cl^- , Br^- , NO_3^- , and SO_4^{2-} . The method separates a specific anion by using a column packed with ion exchange resin and an eluent composed of a mixture of sodium bicarbonate and sodium carbonate. The anion is converted to an acid form by ion exchange and its concentration is determined from the conductivity of the acid produced. The method is very accurate with few interferences.

For other inorganic parameters listed in Table 3.14, the following methods should be used:

- Total Dissolved Solids - Gravimetric method;
- Total Suspended Solids - Gravimetric method;
- Alkalinity - Automated Potentiometric Titration;
- Mercury - Flameless Atomic Adsorption.

(2) Analysis of Organic Parameters

For the simple organic parameters oil and grease and total organic carbon (TOC), the following methods should be used:

- Oil and Grease - Gravimetric method whereby dissolved or emulsified oil and grease is extracted from acidified water by petroleum ether or trichlorotrifluoroethane;

- Total Organic Carbon - Infra-red Analysis whereby organic carbon is determined by the difference between total carbon (infra-red detected CO₂ produced in high temperature combination) and inorganic carbon (infra-red detected CO₂ produced in low temperature acid decomposition).

To determine the concentration of individual trace organic contaminants, two methods have been chosen. The first method, the purge and trap technique, is a gas chromatograph/mass spectrometry (GC/MS) technique suitable for detecting volatile organics. The method is described in EPA Test Method #624. In this method, the contaminants are purged from a water sample with a stream of finely divided bubbles of an inert gas, trapped on the sorbent Tenax, thermally desorbed into a packed gas chromatographic column and detected with a mass spectrometer repetitively scanning from 33 to 260 atomic mass units (amu) at approximately 5 - second intervals.

The second method, the liquid-liquid extraction technique, is suitable for determining organics soluble in dichloromethane (DCM). The method is described in EPA Test Method #625 (1982). Briefly, the method partitions contaminants in the sample between pH adjusted water and an organic solvent, DCM, by mixing the two liquid phases in a separatory funnel or a continuous extractor. After separate partitions are formed at pH 12 and pH 2, the individual methylene chloride solutions are either analyzed separately or combined and analyzed. In either case, the organic solvent is dried, concentrated to a low volume, and an aliquot injected into a fused silica capillary gas chromatography column. Mass spectrometric detection is completed using repetitive scanning from 35 to 450 amu at approximately 1- to 2 -second intervals.

These methods for organic analyses have been selected because they are highly reliable in the identification of a number of the selected organics plus any other organics that are susceptible to the sample preparation and chromatographic conditions. In general, the methods will detect any compound with molecular weights less than 260 (Method #624) or 450 (Method #625). These methods also provide identification of a wide variety of parameters simultaneously in a cost effective manner.

(3) Analysis of Stable Isotopes

The analysis of stable isotopes shall be limited to those isotopes that are commonly used in hydrogeologic studies namely ^2H (deuterium), ^{13}C , ^{18}O , and ^{34}S . Isotopic analyses are routinely conducted by only a few laboratories in Canada (i.e., University of Waterloo, and Chalk River Nuclear Laboratories) and therefore the exact analytical protocols are dependent on the laboratory conducting the analyses.

^2H and ^{18}O are usually conducted by mass-spectrometry. The method requires samples that have not been sampled due to evaporation. When properly conducted, the technique should be accurate to $\pm 0.1\text{‰}$ (‰, parts per thousand as compared to the difference of a reference standard. Results are usually reported in the δ per mil notation with respect to the standard where $\delta^2\text{H} = ((\text{Rx}-\text{Rs})/\text{Rs}) \times 1000$ and Rx and Rs represent the $^2\text{H}/^1\text{H}$ ratios of sample and standard respectively) for $\delta^{18}\text{O}$ and ± 1.0 for $\delta^2\text{H}$. For deuterium, the isotopic content can be determined by a double - collecting mass spectrometer with semi-automatic inlet and with a vapor-sampling device directly connected to the mass spectrometer via a uranium reduction furnace (Fritz et al., 1979). The determination of ^{18}O can be completed indirectly by mass-spectrometry analysis of the $^{18}\text{O}/^{16}\text{O}$ ratios in carbon dioxide equilibrated with the water sample. The reference standard for ^2H and ^{18}O is Vienna Standard Mean Ocean Water.

For ^{13}C analysis, the carbonate in the water sample is precipitated as BaCO_3 in an alkaline medium (i.e., carbonate - free NaOH and reagent grade $\text{BaCl}_2 \times 2\text{H}_2\text{O}$). In the laboratory, the carbonate is removed as CO_2 through acidification of the precipitate with phosphoric acid or from solution by an acid stripping process. The resulting CO_2 is analyzed on a mass-spectrometer and compared to the reference standards PDB (carbonate standard derived from Belemnite from the Pee Dee Formation of South Carolina) or National Bureau of Standard (NBS - 20, Solenhofen Limestone).

^{34}S is determined in a manner similar to ^{13}C . A sulphate precipitate is collected in an alkaline medium such as BaSO_4 . If reduced sulphur is to be analyzed, a precipitate is produced in Cd acetate or Zn acetate to form insoluble sulphides. The residual water after removal of the precipitate can be used for sulphate precipitation. The sulphate precipitation is transformed to SO_2 and analyzed by mass spectrometry. The reference standard for ^{34}S is the Canyon Diablo meteorite - troilite phase.

3.3.3.6 Quality Control/Quality Assurance Program. To ensure the integrity of water quality results in any geochemical program, it is necessary to develop and use a quality control/quality assurance (QC/QA) program. The QC/QA program has the purpose of providing a quantitative measure of the accuracy and precision of the geochemical results.

This program starts with sample control procedures in the initial sample collection. Sampling protocols define the equipment cleaning and sampling procedures so that all samples are collected in a manner that allows comparison. Consistent sampling protocols reduce uncertainties in the analytical results caused by equipment contamination or methodology changes.

In the laboratory, QC/QA procedures are of primary importance. Laboratory control methods should include the following:

- Control samples;
- Replicate samples;
- Certified reference samples;
- Interlaboratory comparisons;
- Laboratory performance evaluation.

Control samples will consist of blanks inserted with the samples at a suggested frequency of one control per ten samples. The number of control samples is a function of the number of samples and the degree of control required. Control samples at a frequency of one to one have been used where samples are collected infrequently but, although this increases the confidence in the laboratory control of each sample, it also doubles the cost. Control samples are usually high purity deionized water or reagent blanks used to monitor any possible sources of contamination found in the analytical method or in the reagents. Often additional control samples are collected from the sampling equipment by running deionized water through it.

Replicate samples provide an indication of the analytical precision and reproducibility of the analytical and sampling procedure. These samples are duplicate samples of the same source which are given different sample numbers (i.e., blind duplicates). The frequency of replicate samples is often one in ten in a large sampling program but may be more frequent as the need arises.

In analyzing replicate samples, it is assumed that the same analytical result should be obtained for each sample; however, there is often variability between the results. This variability results from the accuracy of the analytical method which may be on the order of plus or minus a few percent. If replicate results frequently exceed the accuracy of the method then the sampling and analytical method should be evaluated to determine the source of error.

Certified reference samples are samples that contain a known concentration of a single or several parameters. These samples are run occasionally to provide an accuracy check of the analytical method. If the method yields values significantly different from the certified reference sample then the technique needs to be refined or the instrument recalibrated. Certified reference samples also provide a check on the analytical precision.

Interlaboratory comparisons are conducted by sending an identical duplicate sample (typically one in ten) to another laboratory for an independent analysis of the same parameters. Care should be taken in this procedure to ensure that the samples are collected in exactly the same manner and that the laboratories use identical analytical techniques. Interlaboratory comparisons often yield a range of values and it is suggested, where possible, to use three laboratories (in total) to reduce the uncertainty with regards to which laboratory is correct. In all likelihood the three laboratories will provide three different values for each parameter; however, all of the values should be statistically comparable.

In general, the performance of a laboratory can be evaluated by comparing all QC/QA procedures using statistical analysis. Most laboratories participate in interlaboratory comparisons which provide an opportunity to refine the analytical procedures.

3.3.4 Hydraulic Testing Program

3.3.4.1 Test Methods

(1) Definitions

The flow of fluids through geologic media was first described mathematically by Darcy (1856) while investigating the flow of water through homogeneous sand filters. Darcy found that the rate of flow (Q) was proportional to both the cross-sectional area (A) and the hydraulic head (h) difference across the filter and inversely proportional to the length (or thickness, x) of the filter. Darcy's observation can be expressed mathematically as:

$$Q = -KA \frac{dh}{dx} \quad (3-1)$$

where K is a coefficient of proportionality known as the hydraulic conductivity and dh/dx is the hydraulic gradient in the direction of flow. In a homogeneous medium, Darcy's Law may be stated as the specific discharge (v) per unit hydraulic gradient where $v = Q/A$. The hydraulic conductivity is a function of both fluid and media properties and can be expressed in terms of these properties as:

$$K = \frac{k \rho g}{\mu} \quad (3-2)$$

where ρ is the fluid density, μ the fluid viscosity and g is the acceleration due to gravity. The rock dependent property is described through the variable k and is known as the permeability or intrinsic permeability of the media.

Darcy's (1856) original observations were based on flow in one-dimension. Because of this, Darcy originally defined his coefficient of proportionality as a scalar quantity. In most hydrogeologic regimes, however, flow is not limited to one-dimension. In multi-dimensional flow systems, hydraulic conductivity, or more

specifically permeability, (because fluid properties are non-directional) is expressed as directional values in the form of a tensor. Unfortunately, few measurements are made to assess the directional values of permeability. Most permeability tests are one-dimensional (e.g., single borehole tests, permeameter tests on cores) and permeability is evaluated as a scalar.

Equations (3-1) and (3-2) were originally developed for porous unconsolidated media. In sedimentary formations, it may in some instances be inappropriate to use porous concepts in describing the hydraulic behavior. In these instances, it may be more appropriate to consider specific fractures. If one assumes that flow through fractured rocks approaches that of flow through parallel planar plates, then, for laminar conditions, the discharge, Q (L^3/T), may be described (for a single set of parallel plates) as:

$$Q = \frac{b^3 \rho g}{12\mu} \frac{dh}{dx} \quad (3-3)$$

where b is the fracture aperture.

By comparison with equation (3-1) the fracture hydraulic conductivity K_f can be defined as:

$$K_f = \frac{\rho g b^3}{12\mu} \quad (3-4)$$

Unfortunately flow through naturally occurring fractured rocks does not usually occur in single fractures but rather through fracture zones having frequencies of tens to hundreds of fractures per metre. In addition natural fractures are not smooth but typically possess some degree of surface roughness. This, together with the

existence of fracture infillings and the non parallel nature of the fractures, has resulted in only partial validation for the cubic law (Equation 3-4) as reported by Witherspoon et al. (1981a).

The equivalent porous media approach is usually valid in most higher relative permeability formations of sedimentary origin (i.e., sandstones). However, in lower permeability formations (i.e., shales, intact limestones), scale considerations may be a concern. That is, the permeability value obtained may be a function of the test interval length (i.e., packer spacing). This will be the case if, as in most naturally occurring fractured rock systems, the fracture spacing and aperture size are irregular. Scale problems in permeability testing are discussed in a subsequent section.

The nature of naturally occurring fracture systems also gives rise to two types of rock permeability, fracture and matrix. As the names imply, matrix permeability refers to the permeability of the intact rock mass, while fracture permeability refers to the permeability associated with either distinct fractures or fractured zones. Bulk permeabilities typically refer to the overall permeability of the rock mass combining matrix and fracture permeabilities. The nature of the test being employed to measure permeability together with the state of the rock mass will determine if the quantity being measured is fracture or matrix or (if bulk) what percentage is likely to be matrix versus fracture. Borehole pressure pulse tests and permeameter measurements performed on cores will typically yield matrix permeability values. Relatively short term field tests conducted in highly fractured rock will most likely yield estimates of fracture permeabilities. These and other tests used in obtaining permeability estimates are described in more detail in Section 3.3.4.2.

(2) In Situ Techniques

The in situ permeability of a geologic media is typically evaluated through the use of boreholes drilled into the formation of interest and involves using various pieces of equipment to isolate specific test zones. The two main groups of isolation devices are piezometers and packer systems.

Piezometers may be regarded as permanent because they act to isolate a selected interval that does not change with time. Piezometers may be constructed in several configurations including a single piezometer, multiple piezometer (several piezometers in one borehole), piezometer nest (a group of single piezometers completed at different elevations), or multiple-port piezometers (ports along the casing can be open and closed to access selected intervals).

Packer systems consist of an arrangement of packers (inflatable flexible glands) which, when inflated, isolate a selected zone in the borehole. Hydraulic testing is usually carried out in an interval in the open borehole which is isolated by one or more packers. Packer systems may be moved along the length of the borehole so as to test different intervals of the formation. Test interval length may also be varied. Pressure and often temperature are monitored in the test interval using pressure transducers and thermistors.

Three configurations of packer systems exist, including single, straddle and guarded-straddle packers. Single packers are used during drilling to test the zone below the drill string between the bottom of the hole and the packer. Straddle-packers consist of two packers at adjustable spacings which are used to conduct hydraulic testing in selected zones throughout the borehole. Problems associated with single and straddle-packer configurations include leakage at the packer seal with the borehole wall (packer leakage) or hydraulic communication through the formation (packer bypass). As a result,

guarded straddle-packers were developed. This configuration consists of four packers in which the inner two isolate the test zone while the outer two isolate zones monitored to detect leakage.

In situ tests can be broadly classified as either single or multiple borehole tests. Each of these categories provide hydraulic conductivity estimates that are representative of different scales. Single borehole tests are usually limited to testing the region in the immediate vicinity of the borehole. Multiple borehole tests, on the other hand, provide permeability estimates over potentially much larger distances - equal to the borehole spacing. Both categories rely on introducing a perturbation to the hydrogeologic system. Multiple borehole tests use essentially the same techniques as single borehole tests. Hydraulic testing techniques are usually further classified on the basis of the perturbation technique, e.g., drill stem test, slug test, pulse test, pump test, injection test, etc. The individual methods are discussed in detail in the following sections.

(a) Single Borehole

Slug Test

A slug test is defined as an "instantaneous change in water pressure of a test interval by injection or withdrawal of a known volume of fluid, swabbing with the drill stem, or by introducing a solid slug of known volume" (ETC, 1985b). The pressure or hydraulic head is monitored as the perturbation recovers to its original value. Slug tests are a transient test and the recovery versus time relationship is characterized by an exponential function. In a slug test water must actually flow in or out of the test interval before a head/pressure change is registered. Slug tests are most applicable to hydraulic testing in rock masses with a hydraulic conductivity between 10^{-9} and 10^{-4} m/s (10^{-16} to 10^{-11} m² at 21°C) (Wilson et al., 1979) as shown in Figure 3.10 but may also be used in lower permeability media. This range of hydraulic

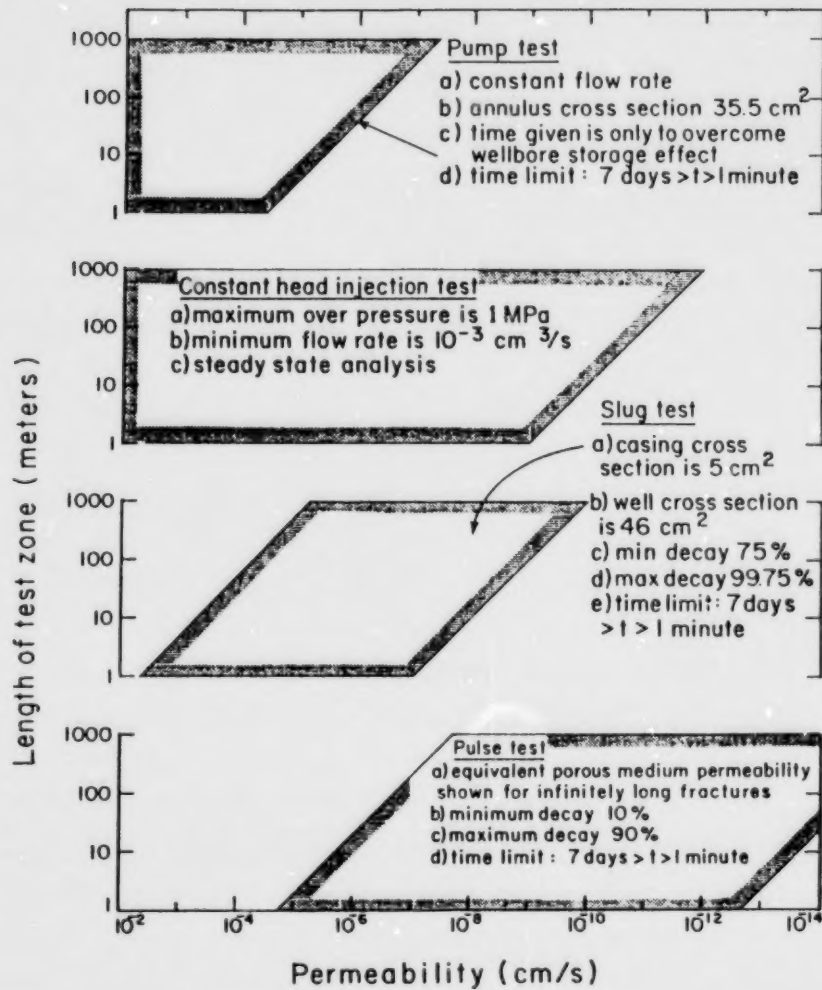


Figure 3.10 Guide to Selection of Well Test Techniques for Permeability Measurement (from Wilson et al., 1979)

conductivities has been confirmed in the Canadian Nuclear Waste Disposal Program as reported in Raven (1980). In low hydraulic conductivity rock a long period of time is generally required for recovery. The difficulties in slug test application may be reduced to some extent by using a narrow diameter borehole (Bredehoeft and Papadopoulos, 1980); however, physical limitations on the size of monitoring equipment set the lower limit for borehole diameter.

In creating the hydraulic perturbation, it is necessary to consider the magnitude of the perturbation relative to the sensitivity of the monitoring equipment. For slug testing, it is desirable to monitor recovery until approximately 70% of the initial perturbation has dissipated in order to accurately match theoretical and observed data. Thus, the initial perturbation should be adequate to ensure that pressure readings can be measured reliably given the limitations on monitoring equipment. However, the initial pressure change should be less than the least principal rock stress to ensure that deformations of the rock mass are small compared to aquifer storage effects (Bredehoeft and Papadopoulos, 1980). Unfortunately, this value of rock stress is usually unknown. Slug tests should be conducted using an initial pressure change just adequate to allow recovery to be monitored. Typical initial pressure perturbations vary from one to ten metres of water (Bredehoeft and Papadopoulos, 1980).

Slug tests may be analyzed using a variety of techniques ranging from analytical solutions to numerical models. Cooper et al. (1967) developed an exact solution to the radial groundwater flow equation for saturated porous media. Inherent in his solution are a number of assumptions including a fully penetrating well screen completed over a homogeneous isotropic aquifer of uniform thickness. In porous media, hydraulic conductivity estimates are generally obtained by matching observed data to a series of type curves. The

value of hydraulic conductivity obtained using this technique is generally fairly reliable although the storage coefficient may be subject to considerable uncertainty. This technique has been applied to fractured rock systems yielding a porous media equivalent estimate of the hydraulic conductivity. The danger of this approach is obtaining a single horizontal permeability estimate that may be a function of the test interval length (i.e., irrespective of fracture distributions).

Slug tests can be used to obtain a measure of formation pressure; that is, as time increases from the start of the test, the pressure in the test interval recovers towards the formation pressure. The time required to reach this pressure is inversely related to the permeability of the test interval. Thus, in low permeability formations, the testing time to obtain an estimate of formation pressure may be extremely long.

Slug tests are, as most hydraulic tests, subject to a number of factors that may influence the ability of the test to obtain a representative permeability estimate. This includes such factors as skin effects, accuracy of equipment readings and depth measurements and compliance of the test equipment. Additional factors that should be considered include the extent of the radius of influence and the appropriateness of assumptions which may be inherent in the analysis technique. These factors are discussed in detail in a subsequent section for both slug and other test methods.

Pressure-Pulse Tests

Pressure-pulse, pulse or piston tests induce a perturbation comparable to the effect of a slug injection/withdrawal test, the difference being that the perturbation is created by causing a pressure change in the test interval by pressurizing a finite volume of fluid rather than actually removing the fluid. Pressure response is governed

by compressibility effects with very little flow of fluid occurring. The duration of the test may be much shorter than other tests because this test relies on pressure (as opposed to fluid volume) dissipations. This is more desirable in low permeability or tight formations where flow to and from the test section occurs at very slow rates.

The pressure-pulse test is applicable over a range of hydraulic conductivities from approximately 10^{-15} to 10^{-7} m/s (Wilson et al., 1979) (Figure 3.10); however, Raven (1980) reported that the test is generally suited to formations with hydraulic conductivities in the low to intermediate range (i.e., 10^{-13} to 10^{-9} m/s).

Pressure-pulse tests require highly sophisticated and accurate downhole monitoring equipment consisting of packers, pressure transducers and thermistors and as a result are much more susceptible to equipment related problems than are other hydraulic testing techniques. Typical problems include erroneous results due to packer compliance (elasticity), air leakage from the pulse piston and thermal expansion and contraction effects generated by thermal gradients. These considerations are discussed in detail in a following section.

Injection Tests

Injection tests consist of injecting fluid to a specific interval which is usually isolated using packers. In most applications, only the steady state portion of the test is analyzed, although it is possible to analyze the transient portion. Injection tests may be classified as either constant head or constant flow tests.

Constant head tests are most common and involve injecting fluid under a constant head while monitoring the flow rate until it stabilizes at a steady state value. The test methodology involves achieving steady state for several different values of constant head.

The constant head test is also known as the Lugeon test, the packer test, constant-pressure fluid injection test, water loss test and water pressure test.

The constant flow test involves maintaining a constant injection rate while monitoring the changes in pressure in the test interval until the pressure measurement stabilizes at a relatively constant value. Steady state will theoretically never occur; however, it will appear to occur when the formation is leaky or intersects a constant head boundary.

Injection tests are applicable over a wide range of hydraulic conductivities from 10^{-12} to 10^{-4} m/s (10^{-19} to 10^{-11} m² at 21°C) (Wilson et al., 1979) (Figure 3.10) with the primary lower limit of measurement related to the inability to measure very small flow rates. Flow rates as low as 0.05 cm³/min have been measured (using bubble flow meters) which led to determination of hydraulic conductivities of 10^{-12} m/s for a 10 m interval (Wilson et al., 1979).

Heish et al. (1983) compare injection tests to those of pressure-pulse tests and found that comparable values were obtained for hydraulic conductivities between 10^{-12} to 10^{-9} m/s. The constant rate test led to slightly higher values when testing formations at the lower end of the permeability range possibly due to the larger rock mass sampled by the injection test over the pulse test.

While the steady state assumption facilitates the calculation of a permeability care must be exercised both in conducting the test (e.g., to ensure steady state has been reached) as well as the subsequent analysis. Doe and Remer (1980) examined the porous media solution of Hantush to illustrate the errors that may occur using a steady state approach. They found that the steady state assumption

leads to an overestimation of hydraulic conductivity by less than an order of magnitude for the most extreme cases and is generally within a factor of two to three of the value obtained from a transient analyses. One difficulty with this (steady state) solution is knowing the correct radius of influence to employ. However, the hydraulic conductivity is relatively insensitive to fairly large changes in radius of influence. The test is rapid to set-up and conduct relative to a slug test and is applicable in both the saturated and unsaturated zones. The test yields an average interval value for hydraulic conductivity. Equipment compliance and wellbore storage effects are not generally observed as the pressure differential is constant. In this test, if flow rates are high, pressure loss along the pipeline to the ground surface due to frictional losses is another important consideration.

Additional factors which may influence the accuracy of injection tests, such as leaky packers, temperature induced pressure responses, skin effects, etc. are discussed in detail in a subsequent section.

Drill Stem Tests

Drill stem tests, commonly performed in the oil industry, involve temporarily shutting in a selected interval using a single or multiple packer configuration. The test involves a sequence of events which yield the formation pressure and permeability, an indication of flow rate as well as facilitating sampling of formation waters.

Once the packer(s) is inflated, a sequence of specific tests is commenced. First, fluid is evacuated from the drill string. Then, a hydraulic perturbation equivalent to a slug test (discussed previously) is created in the test interval by opening the isolated interval to the lower drill string pressure. Formation water then

flows into the tubing string such that this portion of the test is referenced to as the "initial flow period". During this period, formation water and/or drilling mud in the test interval flows into the tubing string in preparation for further hydraulic testing and water quality sampling. Also, the flow rate into the tubing/drilling string is monitored for subsequent permeability calculations. It should be noted that the theoretical basis upon which pressure build-up tests are analyzed is based on a constant flow rate during the initial and subsequent flow periods (Earlougher, 1977). However, the flow rate actually decreases with time with an average used in calculations. This assumption can cause significant errors in high-productivity wells (Earlougher, 1977) but can be accounted for in a modified analysis. Following the initial flow period, the test interval is shut in (isolated from drill string fluid pressure) and the transient pressure recovery or build-up is monitored over time (analogous to a pulse test discussed previously). This portion of the test is continued with the objective being to obtain an estimate of formation pressure. In addition, the exponential pressure recovery is used in calculation of permeability typically using a Horner plot of pressure versus $(t_p + \Delta t) / \Delta t$ where t_p is the duration of the initial flow period and t is the time since start of the pressure build-up (analysis techniques for pressure build-up tests are discussed in detail in Earlougher, 1977). The build-up period is typically continued until some predetermined change in pressure per unit time is observed or until a ceiling on allowable test time is exceeded.

The sequence of flow and build-up periods is usually repeated at least once as the initial flow and build-up periods are intended to relieve the potentially high hydrostatic mud pressure and return the test interval to formation pressure.

Wellbore storage is not usually significant unless a large test interval (i.e., packer spacing) is used or unless the formation is of relatively low permeability. However, wellbore pressure history,

temperature and skin effects are factors which may be significant in the test analysis. If this is the case, a much more comprehensive data analysis methodology is in order. By utilizing numerical methods, it is possible to more reliably assess formation pressure and permeability by accounting for temperature changes during the test borehole history and skin effects. A model to perform these simulations has been developed and applied to hydrologic testing in crystalline rock environments as part of the Swiss Nuclear Waste Disposal Program (Grisak et al., 1985).

The assumptions inherent in the drill stem test are analogous to those of the slug and pulse test and include:

- constant flow rate;
- infinite reservoir;
- horizontal flow;
- negligible gravity effects;
- homogeneous and isotropic porous media;
- single fluid of small and constant compressibility;
- Darcy's law applies;
- porosity, permeability, viscosity and total compressibility are independent of pressure.

Deviations from these criteria are insignificant or can often be accounted for in the test analysis. In most instances, it is expected that the in situ hydraulic characteristics in the study area will be adequately assessed using a drill stem test as the testing method. It is this method which is recommended at this point in time given the information available on the hydrostratigraphy. Modifications in the proposed testing technique may be required at a later date once the specific test site has been selected and the range of the hydraulic properties is better defined.

(b) Multiple Borehole

The single hole test methodologies discussed in the previous section have, in a number of instances, been modified to involve multiple hole tests. The rationale for multiple borehole tests is to characterize the three-dimensional permeability tensor as opposed to the one-dimensional fracture or average two-dimensional radial permeability obtained with the single well tests. In addition, multiple hole tests or interference tests are representative of a much larger rock volume, the scale of which is related to the distance between the test and monitoring wells. Thus, multiple borehole tests tend to be more representative as the volume of rock sampled is larger and conditions in the immediate vicinity of the borehole (i.e., borehole skin effects) have less of an impact on test results.

For this feasibility study, the advantages to performing multiple borehole tests are not considered to be sufficient to offset the additional costs of drilling and testing associated with multiple borehole tests. Anisotropies in permeability can be assessed, to a certain degree, by studying cores. The variations in permeability in the horizontal plane can be further quantified by analyzing oriented cores. This level of detail is considered sufficient to fulfill the objectives of this program. As a result multiple borehole tests will not be discussed further. The work of Snow (1966), Louis (1974), Hsieh et al., (1983) are recommended regarding multiple hole injection tests. Pump tests have been studied by a larger number of researchers whose work is summarized and discussed in an excellent paper by Gringarten (1982). Further large scale methods for assessing permeability are the macroscopic hydraulic conductivity tests described by Wilson et al. (1979) and the fracture sampling method described by Snow (1966) and Romm and Pozinerko (1963).

(3) Laboratory Test Methods

Hydraulic conductivity testing in laboratories is oriented towards assessing the hydraulic properties of individual fractures and cores. Laboratory test methods, in many instances, consist of essentially the same methods as those used in the field except that the test environment is more readily monitored and/or modified. The following sections discuss the most widely used laboratory test methods.

(a) Permeameter Tests

Permeameters may be classified as either a constant head permeameter or falling head permeameter.

For constant head permeameter tests, the head and consequently flow rate is kept constant and the change in hydraulic head across the test sample is monitored. This test is used in more permeable media and is reported to be best suited to samples with hydraulic conductivity greater than 2×10^{-6} m/s (Klute, 1965); however, Trimmer et al. (1980) suggest that the range of application of the test, in intrinsic permeabilities, is 10^{-11} to 10^{-18} m² (10^{-4} to 10^{-11} m/s at 21°C).

Constant head or pressure tests are typically performed by the oil industry using air as the fluid. A similar methodology is adopted in which a constant flow rate, measured using a calibrated orifice or other suitable flow measuring device, is passed through the core sample and the pressure drop across the core is measured. This method is discussed in detail in API (1960).

The constant head tests used in the laboratory are analogous to those used in the field with the exception that the laboratory version is an assessment of the one-dimensional properties of the sample whereas the in situ version samples radial properties. The sample is positioned in a cell and the flowrate is monitored for constant pressure gradient across the sample. Once steady state conditions are achieved, the results are recorded and analyzed.

Forster and Gale (1980) applied the constant head (injection) test to a core of granite with a single natural fracture parallel to and centered in the core axis. The results were found to be comparable to pressure-pulse testing on the same core.

The falling head test is a transient test in which the water level is dissipated with time in a water column connected to and draining through the sample. This test is used for material of lower hydraulic conductivity than the constant head test. The use of this method for hydraulic conductivity testing in fractured media is not well documented in the literature.

(b) Pressure-Pulse Tests

Pressure-pulse laboratory tests are again similar to those conducted under field conditions with the difference being that the hydraulic properties are indicative of only the direction parallel to the axis of the core sample. Laboratory tests are representative of hydraulic properties at the scale of the sample size. Applicability to a larger rock volume should be verified by field testing.

Laboratory pressure-pulse testing is useful in that it can be used to quantify the effects of packer compliance which may subsequently be factored out of field test observations. Through

pressure-pulse testing of a sample with a natural fracture, Forster and Gale (1980b) found compliance effects lead to an underestimate of hydraulic conductivity by a factor of up to two.

Pressure-pulse tests were first widely used by Brace et al. (1968). The technique developed by Brace et al. is reported (Trimmer et al., 1980) to be applicable to assessing intrinsic permeability in the range between 10^{-17} and 10^{-21} m^2 (10^{-10} to 10^{-14} m/s @ 21°C) to within 5%. The test was modified slightly by Trimmer et al. (1980) to determine intrinsic permeabilities in the range of 10^{-20} to 10^{-24} m^2 (10^{-13} to 10^{-17} m/s @ 21°C). Test modifications involved curtailing testing prior to reaching equilibrium due to the long time required for equilibrium to be established (two weeks to six months). The test ceased when pressure changes were less than 0.1 MPA in one week. Trimmer et al. (1980) estimated that this introduces an error of less than 10%.

Analysis of pressure pulse tests may be conducted using either an analytical solution which neglects storage or a numerical solution which accounts for storage. The storage term may be neglected without affecting the analytical results when the sample volume is small relative to the reservoir volume. The value of hydraulic conductivity is obtained by matching observed to predicted pressure responses. Trimmer et al. (1980) recommend matching data on the steepest portion of the curve as the thermal transient induced by the initial pressurization has likely dissipated by this time. Furthermore, this portion of the curve gives maximum resolution and is relatively insensitive to the storage term.

Permeameter based tests are considered appropriate for characterizing the hydraulic properties of most cores obtained in the testing program. In some instances, pressure pulse tests may be more desirable in lower permeability media. Also pressure pulse tests should be used in assessing borehole compliance effects.

(4) Influencing Factors

In evaluating or measuring the hydraulic characteristics of geologic media, a complex system of physical variables is typically idealized to simplify analysis of data. However under certain circumstances, the assumptions inherent in a simplified analysis are not valid. For this reason, it is prudent to discuss the influencing factors which affect the measurement of hydraulic characteristics in terms of their potential impact on results.

(a) Borehole Pressure History

The pressure within the borehole (referred to as annulus pressure) after drilling a test interval will, in general, be different from the in-situ formation pressure. This pressure difference results in the development of a "pressure skin" surrounding the borehole. The net effect of the pressure skin developed during the drilling and pretest period is the development of testing conditions that do not meet the assumptions involved in data analysis methods using type curve or computer implementation of analytical solutions. For instance, the pressure recovery in the interval will not be simply related to the recovery to in-situ formation pressure from an initial pressure at the start of the test. The pressure skin developed during drilling and prior to testing will strongly affect the pressure recovery curve. The analysis of packer tests using type-curve or analytical solution methods could therefore yield incorrect hydraulic conductivity estimates under conditions where the annulus pressure and formation pressure are different. Advanced analysis methods (e.g., the hydraulic test analysis program, GTFM, developed by INTERA and described in Grisak et al., 1985) may be utilized, where necessary, to incorporate the borehole history effect and, therefore, yield more accurate hydraulic conductivity estimates from the test data analysis.

Hydraulic testing procedures can be developed in the field program that take into account the magnitude of the annulus and formation pressure and consequently designed to minimize the borehole history effect. Pulse and slug tests or drill stem tests should be conducted with an initial strong pressure pulse or head differential in comparison to both the annulus or formation pressure or the difference between them. Also, a long period open to annulus pressure conditions can cause a sufficiently large pressure skin to develop such that, for the purposes of permeability determination, the annulus pressure can be assumed as the "reference" or pretest pressure. The field program can be designed such that hydraulic tests will minimize borehole history effects and reduce the uncertainty in the interpreted permeability.

Borehole history effects are significant in the measurement of formation pressures. For this reason, it is essential to perform pressure measurements as soon as possible following drilling into an interval. Borehole pressure history is also significant in the long term monitoring of formation pressures. When a well is completed (cased) following drilling and testing, the pressure in the completion interval is influenced by the initial formation pressure, the tests performed and the length of the time and pressures within the open borehole. The pressure recovery time within the test interval can be estimated to equal the total time in which the borehole was open following drilling. This time lag could amount to several months to a year for a new hole in order for all testing programs to be performed. The recovery time also poses a severe restriction on the use of existing uncased boreholes which have been open for a great length of time (i.e., greater than a year).

(b) Thermally-Induced Borehole Pressure Response

Temperature can influence the hydraulic conductivity of a medium in a variety of ways. Hydraulic conductivity is dependent on fluid properties such as density and viscosity which are functions of temperature as well as those of the porous medium. For water, viscosity changes may be significant over relatively small temperature changes, but the magnitude of density variations for the range of temperatures likely to be encountered in most environments is substantially less. Variations due to changes in fluid properties may be removed if one considers solely the permeability of the medium. However, even for this case, the existence of a number of mechanisms complicates the observed relationship between permeability and temperature. These mechanisms have been identified by a number of researchers and include dissolution and precipitation of minerals, fracture closure due to thermal expansion and thermally induced cracking.

Borehole pressure changes during hydraulic testing as a result of nonisothermal testing conditions may have a significant affect on the interpretation of the hydraulic response in low permeability formations. In a closed or tight interval (i.e., low permeability) a small change in temperature can result in a significant pressure response. During and subsequent to drilling a test interval, a temperature profile is developed into the formation in response to the differential temperatures between the borehole fluid and the rock in a manner similar to a pressure skin. The net effect of the temperature profile is a variation in the borehole fluid temperature during the hydraulic testing period. These temperature variations result in significant pressure changes during pulse testing (i.e., under shut-in conditions), especially in low permeability formations as a consequence of the thermal expansion (or contraction) of the fluid.

Pulse injection or withdrawal (build-up) tests are conducted on lower permeability zones because they allow the tests to be conducted more rapidly as compared to slug injection/withdrawal tests or drill stem tests discussed earlier in this section. Varying-temperature conditions existing in any zone requiring pulse tests will likely result in significant thermally-induced pressure responses. In contrast, the pressure response in a high permeability zone is relatively insensitive to temperature changes. The insensitivity is due to the relative ease with which a high permeability zone dissipates any pressure changes, providing the zone has sufficient lateral extent to accommodate the pressure changes. It should be noted that testing of higher permeability zones would generally utilize slug tests, which are not conducted under shut-in conditions, and therefore are not affected by thermally-induced pressure changes.

Analysis methods have been developed by INTERA (Grisak, et al., 1985) and used, where necessary, to account for thermally-induced pressure effects to allow more accurate formation pressure and hydraulic conductivity estimates to be determined from the test data. However, the representativeness of the temperature response measured at the transducer probe depth of average temperature conditions within the test interval is an area of uncertainty. It should be noted that the temperature transducers should be located within the packed-off interval and the transducers and the tool should be in temperature equilibrium with the borehole fluid prior to the start of testing. In this manner, accurate temperatures representative of the test interval will increase confidence in the interpreted results. Much of the uncertainty associated with the formation pressure and hydraulic conductivity determinations in low permeability zones conducted during or immediately subsequent to the drilling phase is a result of the

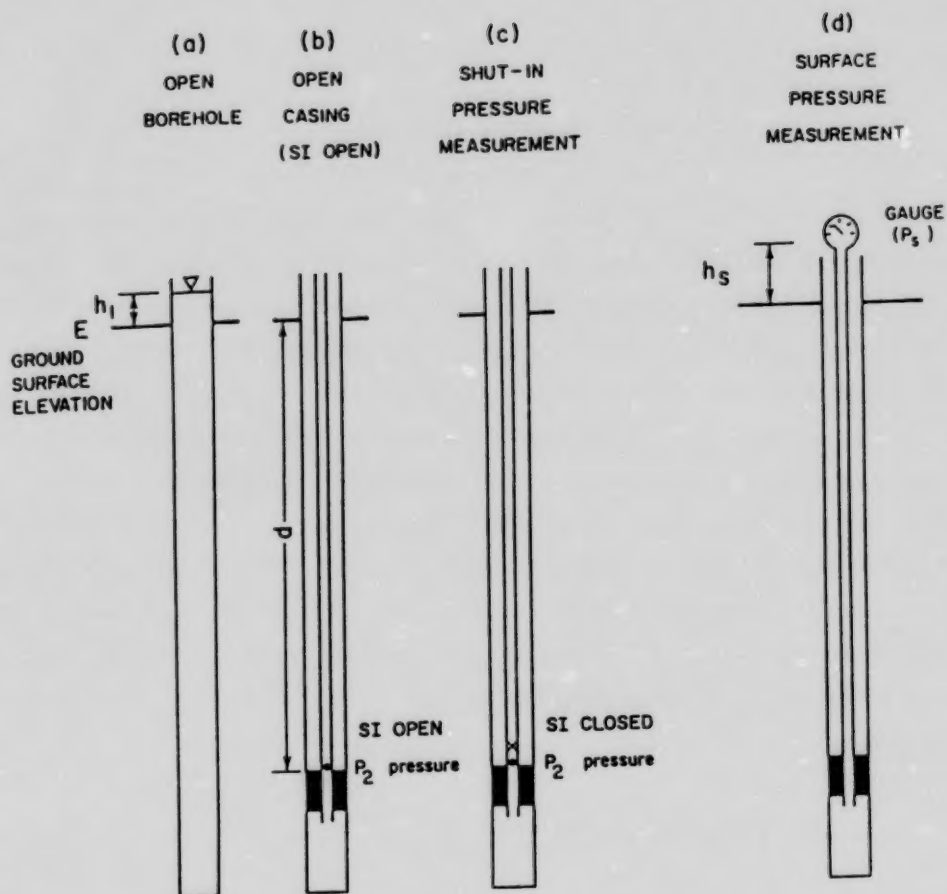
uncertainty in the temperature response. Testing procedures will be recommended that minimize the thermal problem. For example, a long borehole period under passive (i.e., nonpumping) conditions can result in a near equilibrium being reached between the borehole and the thermal skin in the formation surrounding the borehole.

(c) Formation/Fluid Response

Calculations involving hydraulic heads and formation pressures require estimates of the borehole and formation fluid densities. Examples of the various field conditions under which formation pressures or water levels may be measured within deep boreholes are shown schematically in Figure 3.11 and include:

- Water levels measured in an open borehole or a partially cased borehole with an open interval at the bottom (Figure 3.11a);
- Downhole pressure measurement with the test interval open to the tubing string above the hydrologic or drill stem test tools (Figure 3.11b);
- Downhole pressure measurement with the test interval closed to the tubing string and shut in below the testing tool (Figure 3.11c);
- Downhole pressure measurement with a gauge connected to tubing extending to an isolated borehole interval (Figure 3.11d).

The variation in fluid density along the length of the borehole and between various formation depths is an important factor affecting the interpretation of representative formation pressures in open boreholes or in any situation in which the fluid density may vary.



PARAMETERS

- E = GROUND SURFACE ELEVATION
- h_1 = WATER LEVEL HEIGHT ABOVE DATUM
- P_2 = TRANSDUCER PRESSURE MEASUREMENT
- B = BAROMETRIC PRESSURE
- d = DEPTH OF MEASURING POINT BELOW DATUM
- h_s = HEIGHT OF GAUGE ABOVE DATUM
- P_s = SURFACE PRESSURE GAUGE MEASUREMENT
- G = GRAVITATIONAL ACCELERATION
- $\rho(z)$ = FLUID DENSITY WITH DEPTH (FUNCTION OF TEMPERATURE, PRESSURE AND SALINITY)

(NOTE: SI REFERS TO SHUT-IN TOOL)

Figure 3.11 Various Field Conditions Under which Formation Pressures or Water Levels are Measured (from GTC, 1983)

The factors influencing fluid density are:

- Pressure;
- Temperature;
- Salinity (dissolved constituents).

For analysis of hydraulic test data for the determination of hydraulic conductivity, the density, viscosity, compressibility and thermal expansion coefficient (for some cases) of the in-situ fluids are required. It is usually assumed that the borehole and formation fluids have the same properties. Measurement of the fluid specific gravity at surface conditions and temperature and pressure at in-situ conditions allow the determination of relatively accurate estimates for density and viscosity for use in hydraulic conductivity analyses. Fluid viscosity and thermal expansion coefficient exhibit the greatest variation with depth because of their strong dependence on temperature. Choice of representative fluid property values during test analyses is necessary to achieve as accurate as possible estimates of hydraulic conductivity.

(d) Equipment Compliance

Rubber packers and O-rings and entrapped air in the system will tend to compress when a pressure pulse is applied during testing. If, for example, the pressure in the interval is increased as in a pulse injection test then the packers will also be compressed causing a slight increase in the test section volume. As the pressure in the interval decreases the packers will slowly return to their original shape. In addition, the packers may be responding to pressure changes in the zones both above and below the test interval. Because the test interval volume is changing due to the compliance effect, the hydraulic response due solely to the formation is difficult to determine.

Another compliance effect is the packer squeeze effect which is caused by extreme weight being applied to the packers during a tool movement. Both compliance effects can significantly affect the accuracy of the results primarily during hydraulic testing in low permeability formations. In order to minimize the effects of compliance, a number of recommendations are developed in the field program design which pertain to:

- Performance of packer compliance tests under both laboratory and field conditions to determine the system compliance. Packer compliance should be compared to a non-compliant packer (i.e., steel plug) in a laboratory test cell prior to field testing. Field compliance effects should be measured using the entire equipment system in a blank section of casing.
- The weight applied during tool movements when using single and double packer configurations connected with drill tubing to surface should be constant during the test and kept to the minimum required to reduce packer squeeze.
- Inflation pressures above annulus pressure should be at least an order of magnitude greater than the maximum pressure differential applied during testing.
- For formations of lower hydraulic conductivity, the significance of compliance effects increases. Therefore at low permeabilities less compliant systems are desirable.

Equipment compliance has been shown to cause at least a factor of two variation in hydraulic conductivity (Forster and Gale, 1980) and it is therefore necessary to quantify compliance effects

during hydraulic testing. Only through detailed laboratory and field compliance testing can these effects be evaluated. By the utilization of careful testing procedures, compliance effects can be minimized.

(e) Scale Considerations

It is usually assumed that the monitoring system is measuring a representative elementary volume (REV) of the hydrogeologic regime. A REV may be conceptualized as the smallest volume of porous or fractured medium for which the measured values of hydrogeologic parameters or processes are representative. It then becomes necessary to ensure that the sampled volume is representative of the media of interest. In porous media, the REV could depend on the degree of interconnection between pore spaces, which depends on such properties as grain size, compaction, lithification or secondary mineralization. In a fractured medium the REV could depend on the fracture frequency, fracture set orientation, fracture length or continuity. The size of the REV is then dependent on the nature of the medium and is specific to the individual parameter.

The measurement of permeability can be greatly influenced by the scale of measurement. It then becomes necessary to choose a measurement scale that is either representative of the rock mass including the fractures or a scale that is specific to individual fractures and blocks of intact rock. For example, a long test interval may include one or several fractures separated by intact rock. Hydraulic tests on this interval may be representative of the rock mass as a whole even though shorter, specific intervals containing fractures may have hydraulic conductivities that are dramatically different. Where shorter intervals are used the results are more likely to be representative of specific fractures (if fractures were present in the intervals). Comparisons between intervals of greatly different lengths (i.e., long versus short test intervals) may result in confusion when representative values of the rock mass are required.

The measurement scale also has a significant effect on the appropriate analytical technique that is required for analysis of the hydraulic tests. If large blocks of rock are tested such that representative values of permeability, porosity and compressibility can be defined, porous media approximations can be used in the analyses. It is expected that a measurement scale will be selected that would allow the use of porous media concepts in hydraulic test analysis.

For test intervals indicating low to intermediate permeability, additional testing could be conducted using a variety of packer spacings and testing depths to derive a more detailed evaluation of the nature of the hydraulic conductivity (i.e., homogeneous zones, discrete fractures, matrix flow only, etc.). However, it must be emphasized that the implementation of such a detailed testing program to provide this information could substantially increase the efforts and costs of the hydraulic testing program.

The length of the test interval compared to the portion (or portions) of the test interval that dominate the head or pressure dissipation during a hydraulic test is an important consideration. Ideally, from a flow conceptualization and analysis point of view, the full test interval should be contributing. However, it is generally not possible to ascertain the most important portions of the test interval and their contributions to the total permeability. As a result, the full test interval length is usually chosen when interpreting the transmissivity and subsequently the permeability of the tested interval. The hydraulic conductivity is calculated as the transmissivity divided by the formation thickness (i.e., portion of test interval contributing to the most significant proportion of the pressure dissipation during the test) within the test interval. The formation thickness is usually assumed as the test interval length. In cases where the formation zone is, for example, a factor of 10 smaller than the test interval length, the interpreted hydraulic conductivity would also be in error by a factor of 10. The net effect of averaging

over the full test interval length is to overestimate and underestimate the hydraulic conductivity in the lower and higher hydraulic conductivity portions, respectively, of the tested interval. This observation illustrates the need to identify the test interval lengths in order to allow a more representative comparison to other hydraulic conductivity evaluations.

3.3.4.2 Testing Methodology. There are two primary parameters to be measured as part of the hydraulic test program. These are:

- Formation Pressure/Hydraulic Head;
- Permeability/Hydraulic Conductivity.

Generally, the most reliable formation pressures are measured during drilling using single packer drill stem tests and permeabilities are measured at a later time using double or straddle-packer configurations.

The methodology for assessing these parameters and the rationale on which it is based are discussed in detail in the following sections.

(1) Single Packer Tests

In drilling into a previously undisturbed stratigraphic horizon it is essential to perform pressure measurements as soon as possible in order to ensure measuring of unperturbed conditions which may be affected by borehole history. Measurement of permeability, on the other hand, may be performed at a later date with no measurable sacrifice in the quality of data.

In order to obtain representative formation pressures, measurements are performed coincidentally with the drilling operation. Typically, drilling proceeds until a high permeability zone is penetrated as indicated by loss of mud pressure. Pressure measurements should be performed in intervals such as these as the pressure build-up is usually relatively rapid (owing to the higher permeability) thus limiting the down-time in drilling. Measurements are performed by first pulling the drill string and lowering a single packer configuration downhole. The packer is inflated against the borehole wall with the bottom of the hole forming the lower limit to the test zone.

The methodology for obtaining pressure measurements is essentially that used in a conventional drill stem test (DST) with some modifications. The pressure change imposed on the test interval during the initial flow period should be larger than the difference between both the annulus pressure (equivalent to the level of fluids in the borehole) and the estimated formation pressure in order that the dominant pressure response is that due to the current test and not previously imposed pressure differentials.

Throughout the duration of the test it is instructive to monitor the pressure response versus time relationship. In this way, potential problems in the test can be identified. For instance, if the pressure response trends towards the annulus pressure, it is likely that packer by-pass has occurred and the packer seal needs to be checked or re-seated. Also, well bore damage is indicated on a plot of pressure versus time. In lower permeability formations, the pressure response is often affected by borehole skin effects, temperature differentials between the borehole fluids, formation and formation fluids and the test equipment as well as by equipment compliance effects. In this situation, it is essential to verify that the

formation pressure observed during the test is representative and not a result of extraneous effects. A number of measures can be taken to avoid or detect these effects. For instance, a confirmatory injection or withdrawal pressure pulse is useful in bracketing the true formation pressure. The confirmatory pressure pulse should result in pressure build-up or fall-off which approaches the suggested formation pressure from the opposite direction (i.e., initial pulse injection followed by a pulse withdrawal).

The temperature within the test interval should be monitored throughout the test to assess any potential thermally induced effects. Tracking the temperature response jointly with the pressure response should provide an indication of whether or not temperature effects are significant. That is, temperature increases will lead to higher pressures such that an observed pressure increase with time may be attributed solely to temperature. Alternatively, a constant pressure observed jointly with an increase in temperature suggests that full pressure recovery has not occurred. In these situations, it is essential to continue monitoring the test interval until a stable situation exists or until a previously determined maximum test duration is exceeded.

Equipment compliance affects are somewhat more difficult to detect in the pressure/time plot. Presumably, laboratory based experiments will have been conducted prior to field studies to quantify compliance behavior. Based on this work, it should be possible to not only assess the likely affect of compliance on the pressure response but also to develop a hydraulic test methodology and equipment which minimizes these effects. For instance, the force applied to the drill string in shutting in the test interval, which is ultimately transferred to the borehole wall by the packers, may be limited to a magnitude just sufficient to operate the testing equipment and not substantially higher values. Packers and downhole hardware should be selected which has minimal compliance effects.

Equipment calibrations are essential in assuring the validity of the data collected and in preventing unnecessary delays in drilling due to test equipment malfunctions. Pressure transducers should be calibrated prior to lowering downhole.

Equipment selected for use in the testing should facilitate the collection of high quality/high resolution pressure and temperature data. Pressure transducers are significantly better than coded discs used in some hydraulic testing tools and are recommended for this program. Downhole sensors should be capable of sustaining shocks and vibrations and have high thermal stability to perform in conditions likely to be encountered during positioning and testing.

Scale and the concept of representative elementary volumes (REV's) was introduced in an earlier section. The effect of test interval length or scale on the single packer tests is a point worthy of consideration. Scale is important to derive both pressure measurements and permeability values from the tests. If a large test interval length is used, it may be that one point in the interval dominates the pressure measurement. Uncertainties in the location of this fracture or bedding plane will cause uncertainties in the calculated hydraulic heads which are on the order of the test interval length. Alternatively, if shorter intervals are used then more test intervals are necessary to monitor each zone in which a pressure response to injection may occur. To alleviate this situation, a compromise must be reached between test interval length and the number of test intervals. This can best be achieved by using a test interval length of 5 to 30 m provided the zones which dominate the pressure response can be identified through hydraulic testing and geophysical logging. In this way, the reference elevation for hydraulic head calculation is known with some confidence and the uncertainty is minimized.

In regards to scale effects on permeability measurements, the test interval length needs to be sufficiently large to sample a REV. This would likely be several fracture zones or planes. This would also likely involve test interval lengths of 5 to 30 m. If further assessments of discrete fracture zones are required, these can be performed as part of the permeability assessment program performed at a later date using multiple packers.

The pressure versus time relationship from single packer tests can also be used to determine formation permeabilities, although this is of secondary concern to the measurement of formation pressure. The pressure response observed in a hydraulic test is dependent on both the formation and the fluid properties. Important fluid properties include fluid compressibility, density, thermal expansion coefficient and heat capacity. In many cases, these values are published as a function of temperature and/or pressure and do not necessarily need to be measured. However, experience has found that it is useful to measure fluid density (specific gravity) of formation waters generated during a test (i.e., during the flow period). This measurement, performed at surface in conjunction with downhole pressure and temperature measurement, generally provides sufficient data for reliable permeability/hydraulic conductivity calculations.

(2) Multiple-Packer Tests

As mentioned previously, multiple-packer tests are used primarily to obtain a measure of permeability/hydraulic conductivity. These tests are performed in open boreholes at some time after drilling for a number of different reasons. First, this time lag offers an opportunity to obtain permeability estimates from the single packer tests and to ascertain their reliability. Secondly, a full suite of geophysical logs can be run and interpreted in the interim. Interpretation of geophysical logs will provide additional guidance

in locating permeable zones which were possibly missed during drilling and may be of interest for permeability measurements. Thirdly, and most importantly, permeability measurements in lower permeability zones, which take a greater amount of time than in higher permeability zones, can be performed without compromising the drilling schedule. The recommended methodology for these tests is discussed along with a number of important considerations in application of the tests.

Multiple-packer tests are also used to assess the hydraulic properties of geologic media through testing in cased holes. The testing is performed through the casing perforations with the test interval length selected to coincide with the length of the casing perforations.

Testing through the perforations is not expected to adversely affect the hydraulic response provided that significant head losses are not created by fluid movement through the perforations. To avoid potential adverse effects, sufficient casing perforations should be made and a test methodology should be selected which results in low velocities through the perforations. It is also advisable to extend the duration of multiple-packer tests in cased holes which have recently been perforated in order to obtain a measure of formation pressure prior to installing long term monitoring equipment.

Double or straddle packers are perhaps the most common form of multiple packers. Straddle packers consist of two packers separately vertically to isolate the test interval. In typical downhole tools (i.e., Lynes hydrological tool), pressure is monitored in the annulus above the top packer, in the test interval and below the bottom packer and temperature is monitored solely in the test interval. Pressure sensors (transducers) above and below the test interval act as indicators of leakage (i.e., packer by-pass) or compliance effects and are thus quite valuable in test trouble-shooting and interpretation.

Guarded packers or guarded straddle packers consist of double packer arrangement with an additional upper and lower packer added on. The primary advantage of the guarded zones is pressure transducers situated in these zones that can be used to detect packer by-pass or leakage. This system for monitoring leakage has a much greater resolution than the double packer system as the pressure above the test zones is not affected by variations in annulus pressure and the pressure below the test zone is not affected by variations in the lower part of the borehole. Thus, pressure changes detected in the guard zones can be attributed solely to leakage problems.

Multiple packer tools such as those described above are lowered downhole on a drill string operated by a workover rig somewhat smaller than that required for drilling. The packers are inflated against the borehole wall and the pressure testing again proceeds similar to a DST as described previously (Section 3.3.4). Many of the same considerations discussed in the previous section (i.e., temperature) are equally applicable to multiple-packer testing and are not repeated here.

In multiple-packer tests, the formation in the vicinity of the borehole has been subjected to an annulus pressure unequal to formation pressure since drilling first penetrated that horizon. Thus, the value for initial formation pressure to be used in test analysis is uncertain. However, it has been found in practice that the annulus pressure is generally adequate as an estimate if the borehole has been open for an appreciable length of time.

Equipment compliance affects may also be significant in multiple-packer systems. However, the force applied to the drill string in shutting in the test interval is now carried by two or more packers as opposed to one. Also, vertical movements in the packer assembly are not likely to result in an increase in pressure in the test interval as the top and bottom of the test interval are fixed with

respect to each other. Thus, it is likely that the compliance effects are somewhat less than in a single packer configuration. Regardless, it is still important to assess the compliance behavior through laboratory tests under a variety of pressure and temperature conditions.

In hydraulic testing with a multiple-packer system, the question of measurement scale arises in selecting a test interval length. In formations such as sandstones or partially consolidated sands where the intergranular porosity is high, scale is not likely to be a concern. However, in bedded formations with thick beds and irregularly spaced bedding planes or fracture sets, scale is likely of greater concern. The existence and characteristics of these formations can be identified from core logging and geophysical tests which will aid in selection of a test interval length. Initially, a packer spacing should be selected which is great enough to sample a representative elementary volume. Thus, the interval length would ideally include several bedding planes and/or fracture zones. It is expected that this would require a packer spacing of 5 to 30 m which would remain constant for all testing throughout the borehole. If it is considered desirable to further assess the permeability of discrete fracture zones, then the packer spacing can be reduced for additional hydraulic tests.

In performing multiple-packer testing, it is possible that formation collapse will occur due to the pressure differentials created during testing of low strength formations. This may be limited to a certain extent by using the minimum required pressure differentials to create a measurable and analyzable pressure response. An indication of the integrity of the test formations will be obtained during single packer tests. In the extreme case, multiple packer testing may have to be eliminated from the testing program. If this occurs, then hydraulic testing will be performed in the completed wells to perform as much of a hydrogeologic characterization as is possible given the circumstances.

3.4 LONG TERM MONITORING

The objective of a long term monitoring program is to characterize subsurface conditions and to develop a data base documenting background information. This includes hydraulic and water quality data which describe baseline conditions in the subsurface. Furthermore, a long term monitoring program needs to provide a basis on which the effect of waste fluid injection can be judged.

The objectives of a long term monitoring program are stated as follows:

- To assess background or unperturbed water quality and formation pressures, and
- To monitor changes in water quality and formation pressures as a result of waste fluid injection.

3.4.1 Performance Requirements

The performance requirements of a long term monitoring system can be derived from discussions provided elsewhere in this report which are restated in terms of monitoring system design requirements.

In Section 2.1.4, the nature of existing waste disposal operations were described in terms of injection horizons and rates. Three injection horizons were identified which are currently being used. In any particular area, no more than two of these formations are currently being used. However, recommendations on preferred injection formations in this report (Section 3.1) suggest that formations different from those now in use are often of greater preference. The implications to a monitoring system are that a capability to monitor two and possibly three injection horizons is necessary. This may involve monitoring conditions in formations which are currently in use

as well as those which have not been used for waste injection to date. This is entirely dependent on the location of the well and whether the site is intended to assess background conditions or monitor the impact of waste injection. Regardless, the need for a capability to monitor all three injection zones exists and needs to be satisfied in the design of the monitoring system.

In Section 2.2.1, a number of possible waste release scenarios are identified. In a number of instances, the potential for upwards fluid migration due to both natural or induced conditions is discussed. Vertical fluid migration may occur due to natural conditions such as fracturing in collapse zones overlying the solution edge of the Prairie Formation. Vertical fluid flow and pressure build-up may be induced by poor well completions, hydrofracturing of confining layers or via inadequately abandoned oil or gas wells. The possibility of vertical migration of waste fluids needs to be addressed in the monitoring system design.

A number of strategies exist to monitoring vertical waste migration. It may be argued that both a pressure response and the arrival of waste fluids will be detected by monitoring in overlying permeable zones (i.e., aquifers). There are several reasons why this approach is not reliable. The pressure response to injection leads the waste fluid front as discussed in Section 2.2.2. Thus any indications of a vertical breach will be initially manifest in a pressure response. In permeable formations, a pressure increase is dissipated relatively quickly and does not build-up very much at any one location. As a result, it is difficult to detect vertical breaches by monitoring in permeable formations. Alternatively, by monitoring in a confining layer overlying the injection zone, the breach can be detected earlier and more readily due to the greater pressure build-up. However, the radius of pressure build-up is much less than for permeable formations. Thus, the monitoring well needs to be situated close to the site of the

breach. Although the most probable breach scenario is generally unknown, situating the monitoring well near the injection well addresses a number of the potential release scenarios identified. Consequently, monitoring of the confining layers above each injection zone at close radii to the injection well is considered an essential capability of the monitoring network.

In most instances of waste fluid injection, it is considered likely that the wastes will migrate predominantly within the injection formation. Heterogeneities within the injection formation are likely to affect the distribution of the waste fluids resulting in an uneven migration rate. This typically results in a fingering of the waste plume as the wastes migrate faster in zones of higher relative permeability with respect to those in lower permeability zones. In certain circumstances, it is conceivable that high permeability zones may exist through which the majority of fluids migrate. This situation is analagous to the simulations performed in Section 2.2.2 in which a 1 m thick injection zone was assumed. In this case, both the pressure build-up and the waste migration rate are significantly greater than when the entire formation is accepting waste. Whether or not thin high permeability zones exist may be addressed through geophysical logging and hydraulic testing. It should also be addressed by completing monitoring wells within the injection formation. By completing monitoring wells in the injection formation, the pressure build-up and waste plume movement can be documented and compared to predicted results. This is essential in obtaining a better understanding of waste fluid migration and in calibrating numerical models to predict the future impact of waste injection.

Within the injection zone, it may be argued that it is not advantageous to use only one monitoring interval. The rationale for this argument is that by completing a monitoring well over the entire formation thickness (which varies up to approximately 400 m in the study area) that the fluid samples obtained will be diluted to very

low concentrations within the wellbore. Also, pressure build-ups in a thin zone may be dissipated through hydraulic connection to adjacent intervals bridged by the borehole. To avoid these problems, a number of monitoring intervals can be completed within the zone of interest. In this monitoring configuration, a pressure and water quality profile can be established over the thickness of the injection zone. This monitoring configuration is much more sensitive in detecting perturbations arising from waste injection or other reasons. However, it is substantially more costly. Numerous monitoring intervals within a formation, such as described here, may be of great interest at particular monitoring sites where the injection formation is quite thick and/or numerous isolated high permeability zones exist within a formation. However, it is difficult to assess this need at this point in time. For this feasibility study, it will be considered sufficient to locate one monitoring well within each of the injection formations. This single completion would intersect the more permeable zones within the formation (as identified from geophysical logs and hydraulic testing). The need for multiple completions with a formation can be assessed once a specific test site is selected and the objectives of the monitoring study are further refined.

3.4.1.2 Pressure Monitoring Capabilities. Formation pressure can be monitored by a number of different means. These methods can be grouped into two main categories; those which measure the depth or elevation of the liquid surface in open borehole and those which measure the fluid pressure at depth adjacent to the monitoring interval. These methods were discussed briefly in Section 3.3.4 and are illustrated in Figure 3.11. In this discussion, the effect of density variations on pressure measurement are identified together with the controlling factors (i.e., pressure, temperature and salinity). These factors need to be incorporated into the design of a pressure monitoring system to ensure that representative formation pressures are being measured.

The simplest and most frequently used method of pressure measurement is measuring the depth to water in open boreholes. This method is subject to a number of uncertainties. Variable density fluid is likely to be present in the borehole, particularly when the column of fluid in the borehole extends over great depths. Natural temperature variations with depth reported as $29.5^{\circ}\text{C}/\text{km}$ (ARC, 1985a), cause changes in the fluid density leading to a fluid level which is difficult to correlate with formation pressures.

The effect of temperature on pressure measurements can be illustrated by considering the height to which a column of fresh water will rise at two different temperatures. Consider first a 1000 m high column of fresh water at 10°C and 1 atmosphere. If the temperature is increased by 30°C , which is the expected range in the study area, the density will decrease from 999.50 to 992.16 kg/m^3 (Dorsey, 1968). This corresponds to a difference in head of 7.3 m. This however is in fact an extreme example and would not be realized in situ. The density required to calculate the true head change can be obtained by integrating the density versus depth relationship as determined by the temperature gradient.

Fluid density variations as a function of pressure are also a factor which need be considered. For instance, the density of fresh water increases by 0.45% when the ambient pressure increases from 1 to 100 atmospheres. This pressure change corresponds to approximately 1000 m of water which is the approximate height to which formation fluids rise in a well completed in the Cambrian/Granite Wash.

The fluid level measured is the result of variable temperature and density along the fluid column and cannot be used to calculate reliable formation pressures.

Another method which is used to calculate pressures is to lower a tube to a known depth below the fluid surface and to measure the pressure required to equilibrate with the column of fluid above the tube. This method is also subject to some uncertainties. The method measures only the pressure due to fluid above the tube which may be subject to density variations as discussed previously. Also, the precise location of the tube and the fluid density below the tube must be known in order to extrapolate the measured pressure to obtain formation pressure. As a consequence, this method should not be used unless the end of the measuring tube is positioned adjacent to the completion interval.

Pressure transducers and transmitters represent an alternative method for pressure measurement. Transducer and transmitter technology has evolved substantially over the last several years such that pressure can now be measured with low hysteresis and high linearity. Pressure measurements to within 0.1% have been achieved for the pressure ranges in which measurements will be required in the long term monitoring program. (Druck, undated product information). To obtain accurate pressure measurements using transducers or transmitters, it is essential to locate the instrument adjacent to the completion zone in order to avoid the affect of density variations in the borehole. Transducers and transmitters are further limited by their need for periodic calibration and their drift in output versus time. These limitations can be overcome by periodic calibration coinciding with other monitoring activities (i.e., sampling, pump maintainance) and drift can be corrected following recalibration. Reliable pressure measurements can be further ensured by adopting a quality assurance program for recalibration and correction of readings. It is concluded that pressure transducers or transmitters should be used for pressure measurement in the long term monitoring program and should be located adjacent to the completion interval.

The pressure measurement program should involve measurements at a frequency not less than quarterly in all formations with continuous measurements desirable in the active waste injection zones. Continuous measurements are recommended in order to assess the pressure build-up response due to short term (i.e., daily) variations in the injection rate as well as to detect irregularities in the pressure history which may be induced by leakage (i.e., hydrofracturing, well completion failure).

3.4.1.3 Water Quality Sampling. The long term monitoring system needs to provide the capability to collect water quality samples at depth in the completed monitoring wells. Formation pressures and consequently the depths to water vary significantly in the different formations of interest. Formation pressures in the study area are lowest in the Cambrian/Granite Wash. In the Cold Lake area, available formation pressures (BP, 1983; Esso, 1985a) suggest that the water level is approximately 300 m below land surface. Equipment capable of retrieving fluid samples from this depth is necessary in the monitoring program.

The monitoring system also needs to facilitate acquisition of representative fluid samples. The ability of a sampling system to acquire representative samples is entirely dependent on the nature and purpose of the sample as discussed in Section 3.3.3. For instance, dissolved gases and volatiles cannot be collected using pumping due to degassing. Ideally, a pressurized sampling vessel would be used. Alternatively, dissolved ions can be sampled using pumps. Nonvolatile organic chemicals can also be collected by pumping but sampling equipment must be selected to prevent sorption of hydrophobic chemicals to equipment surfaces. As a result of these considerations, it is evident that no one sample collection method is ideal and that some trade-offs may be necessary.

Prior to collecting fluid samples, the fluid which has been standing in the borehole must be removed due to possible chemical alteration by interaction with the well casing, the atmosphere or the pack material. Scalf et al. (1981) recommend that 4 to 10 well volumes be removed prior to sampling to ensure collection of representative fluid samples. In deep boreholes, this represents a significant volume. For a 6 inch diameter well with 1000 m of water, between 71 and 177 m³ of fluid need be removed from the well. This represents a substantial volume of fluid which must be removed from the well prior to sampling. This could be reduced by consideration of a smaller diameter borehole. Possibilities for removing borehole fluids include pumping, bailing and swabbing. Pumping requires that a high lift pump and piping to surface be placed in the borehole. All three operations require a workover or service rig to lower equipment up and down the well.

As an alternative, a packer system can be utilized to isolate the test zone from the remainder of the well. In this manner, the volume of fluid to be purged is only that contained by the packer system, a volume substantially less than that contained within the entire well. A packer system can be connected to a downhole pump to provide both a purging and a sampling capability. Furthermore, a sample cylinder could be attached to facilitate collection of a sample for dissolved gas analysis. A system of this type avoids the need for removal of extensive quantities of water from the well annulus.

Water quality samples should be collected annually from all monitoring horizons. It is expected that this sampling frequency will be adequate in terms of identifying baseline conditions and detecting trends in water chemistry. In zones of active waste injection, it may be desirable to monitor at more frequent intervals in order to fully characterize the migration of the waste front. This would provide data on waste fluid migration properties such as retardation and dispersion

which is valuable in assessing the impact of waste fluid injection. The need for monitoring at this level of effort would only be necessary at selected horizons and would be decided on an individual case basis.

3.4.2 Well Completion Alternatives

3.4.2.1 Single Zone Completions. The possibility exists to monitor pressures in a number of stratigraphic zones by utilizing several wells. These wells may include only existing wells or may involve the drilling of one or more new wells. Whether the wells are new or old does not affect the well completion and monitoring performance which is the subject of this section. The implications of using new versus old boreholes are discussed in a subsequent section.

The number of possible well completions to fulfill the performance requirements outlined in the previous section are relatively few. One such system is a combined packer/pump/transducer system which is dedicated to the monitoring well (see Figure 3.12). Pressure can be monitored on a continuous basis and periodic fluid samples can be obtained by pumping.

The requirement to be able to lift 300 m of fluid is somewhat of a limitation on pump performance which may affect the feasibility of this design. It may be necessary to utilize two or more pumps in series to achieve this required lift. However, submersible pumps are commercially available to achieve lifts in this range but these are generally a minimum of 7.5 to 10.0 cm in diameter. Thus, this system is not feasible for small diameter boreholes.

The advantage of the packer in the packer/pump/transducer configuration is that it reduces the purge volume requirements prior to sampling as well as the time lag in pressure response. The entire configuration would need to be removed periodically to obtain pressurized fluid samples and/or to calibrate the pressure transducer. The frequency with which this is performed is dependent on the behavior of the transducer but should not exceed one year.

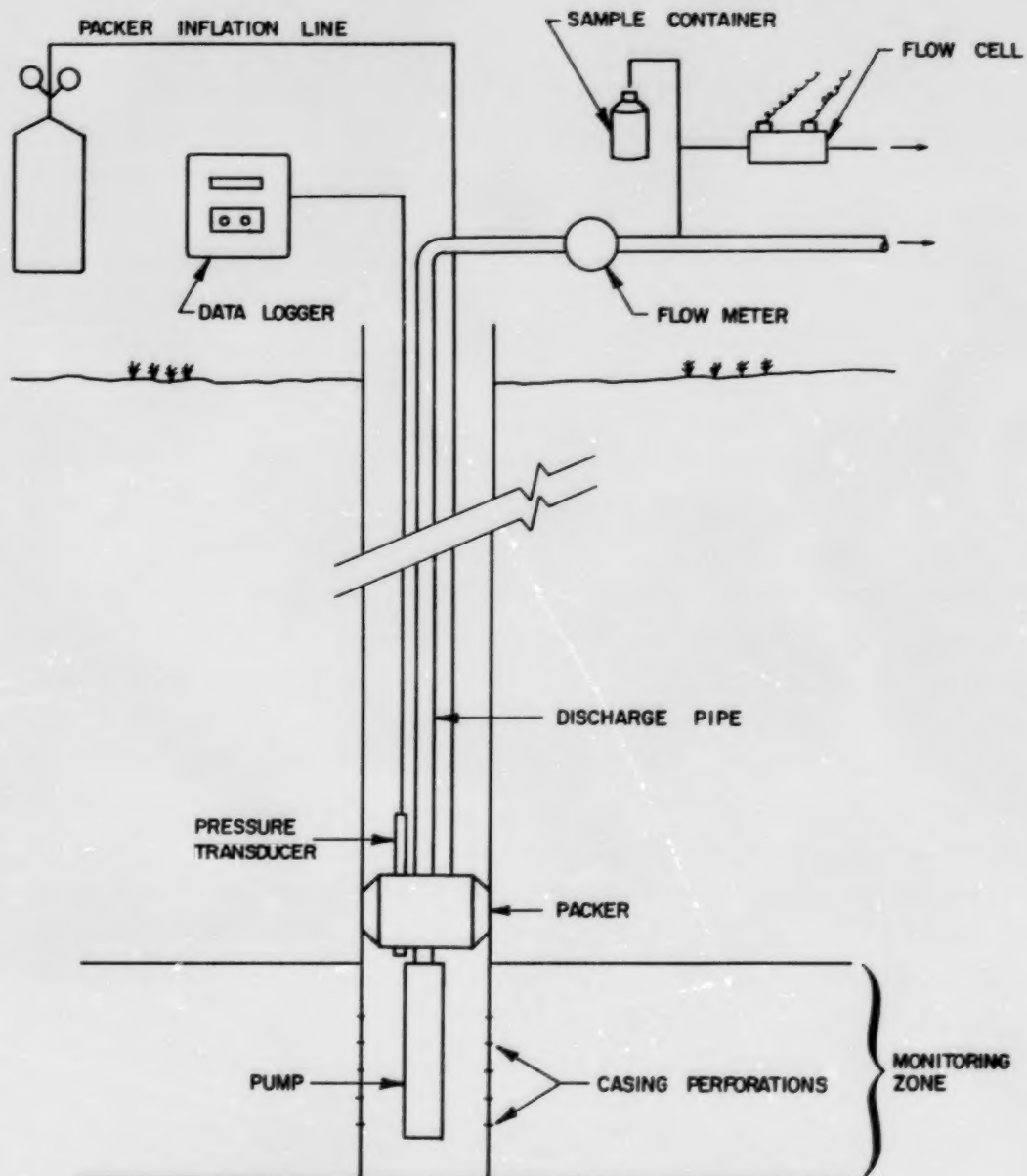


FIGURE 3-12 PUMP/PACKER/TRANSDUCER CONFIGURATION IN PLACE IN A WELL COMPLETED IN A SINGLE MONITORING ZONE

Potential problems with this configuration include firstly the operation and maintenance of pumps in a corrosive brine environment. Situating the sampling pumps in this environment on a continuous basis is likely to result in extensive corrosion and/or degradation of pump parts, discharge line and electrical components. This can be overcome to a certain extent by using corrosion resistant components (i.e., stainless steel) but at a premium price. Secondly, a pump discharge line and electrical cable must be lowered downhole each time the pump is replaced. This involves a significant time period to assemble and disassemble the discharge pipe.

An alternative method is to place a dedicated packer/transducer or packer/transmitter configuration in each well adjacent to the test interval. The packer and transducer would be suspended on a wireline bundled with a transducer cable and packer inflation line as shown in Figure 3.13. Fluid sample acquisition would involve removing the packer/transducer configuration to facilitate evacuation of the wellbore fluids. Evacuation would most likely be performed by swabbing. A series of pressurized sample cylinders is then lowered downhole to collect a fluid sample at formation pressure. This configuration is amenable to use in wells of small and large diameters. Furthermore, this method avoids the need for a dedicated pump in all monitoring wells although the volume of water to be purged is somewhat larger than for the packer/pump/transducer configuration. Pressure measurements are free of time lag and density effects.

To minimize the volume of water to be evacuated when utilizing the packer/transducer configuration in the case of a large diameter well, a permanent packer suspended on a narrow diameter tubing string is advisable. Both pressure monitoring and fluid sampling would be performed through this tubing. If the casing size can be selected during well construction, then it is advisable to use a small diameter casing to avoid large purge volumes.

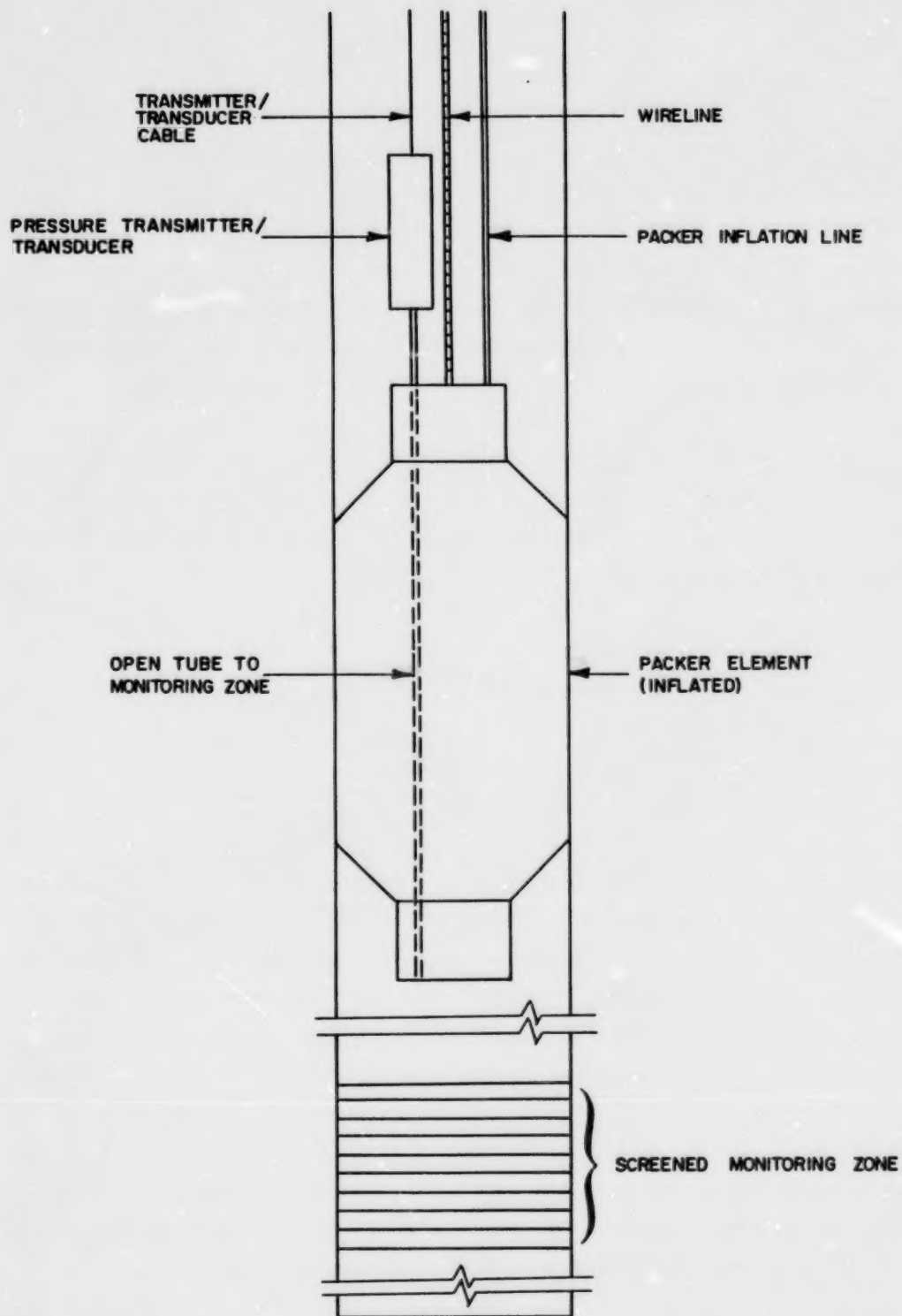


FIGURE 3-13 TRANSMITTER / PACKER CONFIGURATION

Of the two alternatives considered, the most desirable is the packer/transducer system as operational problems are expected to be minimal and it is not necessary to purchase dedicated pumps for all wells and the system can be used in wells of all diameters. If this system was adopted for use then it would be installed in six individual wells completed in each of the three injection zones and each of the three confining units overlying these injection zones as discussed previously.

3.4.2.2 Multiple Well Completions. The well completion possibilities for monitoring a number of zones in a single borehole in deep sedimentary basin are relatively limited. Three systems have been identified as follows:

- Multiple Packer System;
- Westbay System;
- Multiple Piezometer Nest.

(1) Multiple Packer System

The multiple packer system consists of a series of packers placed between perforated intervals in the borehole as shown in Figure 3.14. Under normal circumstances, only the uppermost interval is accessible for pressure measurement and/or sampling. Pressure measurement in this interval would ideally be performed on a continuous basis using a dedicated packer/transducer configuration placed just above the test interval (Figure 3.13). Periodic water samples would be collected in a similar manner to that described previously for a single well completion. That is, the packer/transducer configuration would be removed, the well swabbed to remove several well volumes and a sample collected using pressurized sample cylinders.

To collect fluid samples and measure pressures in underlying formations, the packer/transducer configuration would be removed from the hole. The uppermost packer (Bridge plug) would then be removed and

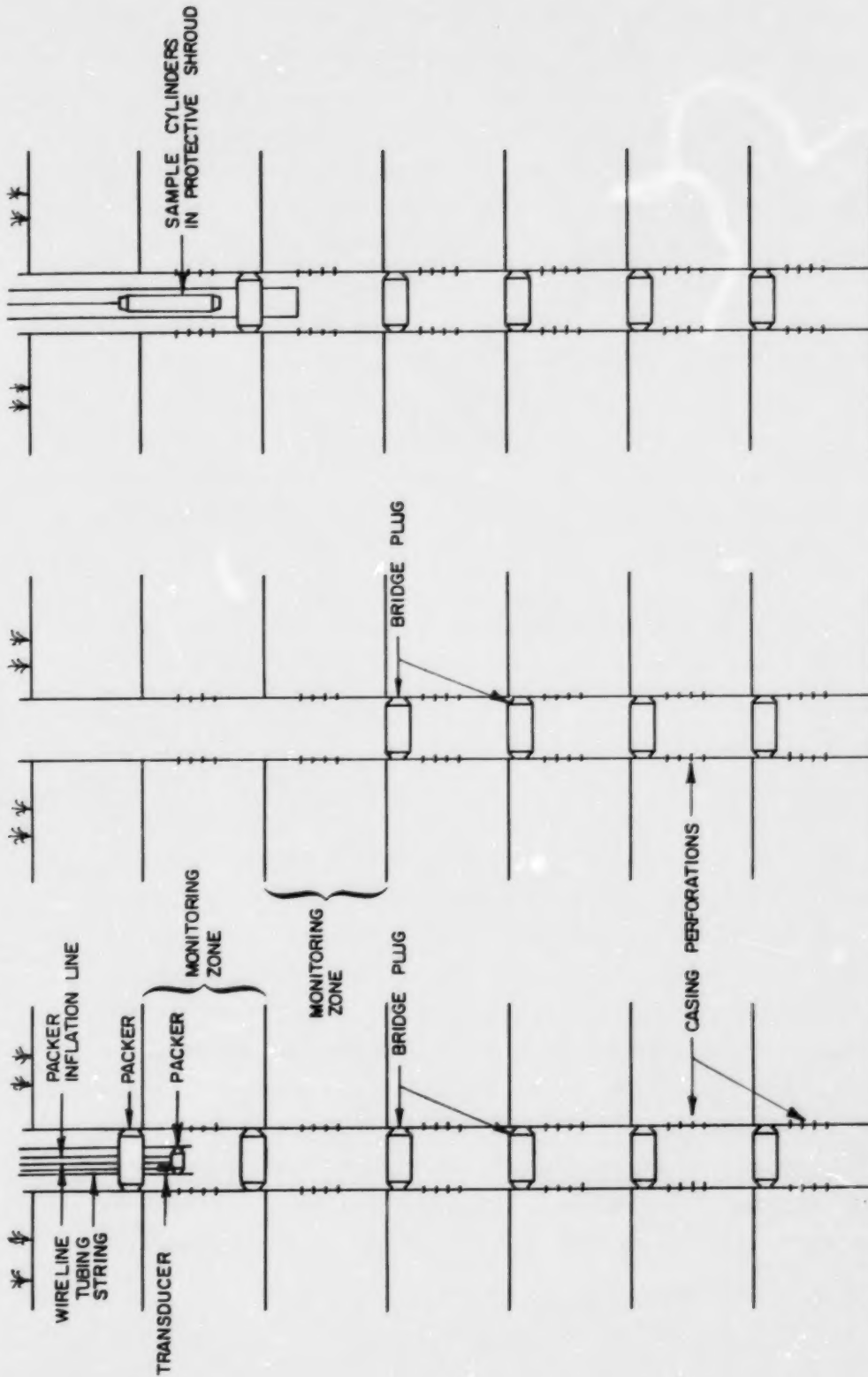


FIGURE 3-14 MULTIPLE PACKER SYSTEM

- (a) Continuous pressure monitoring in uppermost zone with sampling capability.
- (b) Uppermost bridge plug removed in preparation for sampling.
- (c) Collecting fluid samples from lower monitoring zone.

replaced with a packer attached to a tubing string (Figure 3.14). The tubing string acts to isolate the upper zones from the zone to be sampled. The fluid in the tubing string is then evacuated until several well volumes are removed and the water quality stabilizes. Swabbing is likely the most effective way of removing borehole fluids in this instance. Once the water quality stabilizes, fluid samples are collected using pressurized sample cylinders lowered in the tubing string to a position adjacent to the test interval.

Once fluid samples have been obtained, the sample cylinders are removed from the tubing string and replaced with the packer/transducer configuration. The packer is inflated and pressure is monitored until a stable reading is obtained. This procedure would be repeated until all zones have been tested. Then all bridge plugs would be replaced to reproduce the original packer configuration.

The multiple packer system is expected to be of high reliability in that it uses proven equipment common to the oil industry. However, collection of a full suite of samples requires a small workover rig and an estimated time of several weeks to a few months. The large time required for sampling is attributed to the introduction of foreign water to the test interval during removal of the bridge plug. As a result of introducing foreign waters, the test interval would ideally be evacuated until water quality stabilizes indicating complete removal of foreign water. The time required for this is largely unknown but could be limited by reducing the pressures in the casing to below formation pressure prior to removing any packers or bridge plugs. This would create a hydraulic gradient towards the borehole and reduce fluid flow to the formation and consequently the introduction of foreign fluids. Further complications in this system arise due to the effect of corrosion of the steel casing on water quality. In similar circumstances, this problem was minimized by utilizing as small a test interval as possible and by monitoring iron

content for stability prior to collecting fluid samples. Periodic maintenance of the packers is also expected to be required. This may involve checking of seals and valves and replacing of the packer element.

(2) Westbay System

The Westbay system was developed by Westbay Instruments Ltd. of Vancouver and is illustrated in Figure 3.15. The system consists of a coupled string of a smaller diameter inner casing with ports available for either pressure measurement and water sampling or pumping. The individual intervals are separated by one or more packers along the exterior of this inner casing. The packers can be inflated against either the borehole wall or on exterior casing. Pressure measurement and water sampling are performed using specially adapted tools which are lowered downhole. The pumping port is also opened and closed using a special tool.

The main advantage of the Westbay system is that pressure measurements and water samples can be acquired relatively quickly from numerous intervals without the use of a workover rig. The selected monitoring intervals are permanently isolated such that no foreign materials/fluids can be introduced. Pressurized water quality samples can be collected for analysis of dissolved gases and volatiles. Also, the flexibility exists to either collect water quality samples from the sampling/pressure port in a sample cylinder or to collect a sample by opening the pumping port and pumping to surface. Alternatively, the test interval could be purged several times by evacuating the casing and opening the pumping port followed by pressurized sample collection from the sampling/pressure port. It should also be noted that the test interval volume is much less than in the multiple packer system such that the volume of water which must be removed to obtain a representative sample is relatively small.

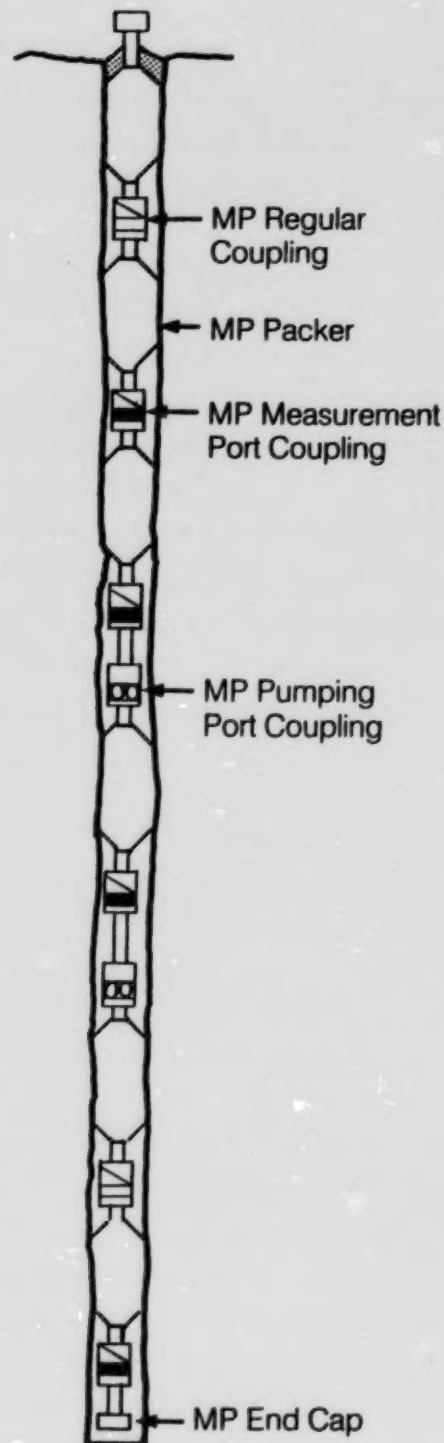


Figure 3.15 Westbay Multiport Monitoring System

A number of questions arise in using the Westbay system, particularly at great depths in sedimentary formations. The system has been used to depths of 1000 m in open boreholes in the Canadian Shield and 1200 m in the Columbia River Basalts (Smith, 1986). In sedimentary formations, the Westbay system has been installed to a maximum depth of 820 m in the Athabasca Sandstone which is substantially less than the 1300 m required for the current application. Consequently, the performance of the Westbay system is relatively unknown in this situation.

In the past, drill holes for Westbay installations in sedimentary strata have been advanced using wireline drilling, air rotary and mud rotary (Smith, 1986). It is likely that drilling mud will be required in this instance to insure the stability of the borehole and to prevent extensive fluid loss to the formation. Previous installations by mud rotary utilized a degradable mud available under the name Revert. This mud degrades to allow flushing from the borehole yet maintains the required properties of a drilling mud during drilling. However, some adverse impacts on water quality may be realized with a mud of this type as it is composed of synthetic organic substances. If a mud such as Revert were not acceptable, then the borehole would have to be flushed prior to installation of the Westbay casing. This would likely be conducted by lowering the casing into place and circulating clean water down through the casing and up through the annulus (Figure 3.16). This would likely result in a relatively clean borehole but would also lead to large volumes of fluid being introduced to the formation which would have to be removed to obtain representative water samples.

Some limitations exist on the operation of the Westbay system at elevated temperatures. The system has been used in field applications at temperatures up to 60 °C but would require modifications to accommodate temperatures in the 100 °C range (Smith, 1986). The 100 °C operating range is considered necessary in both monitoring and

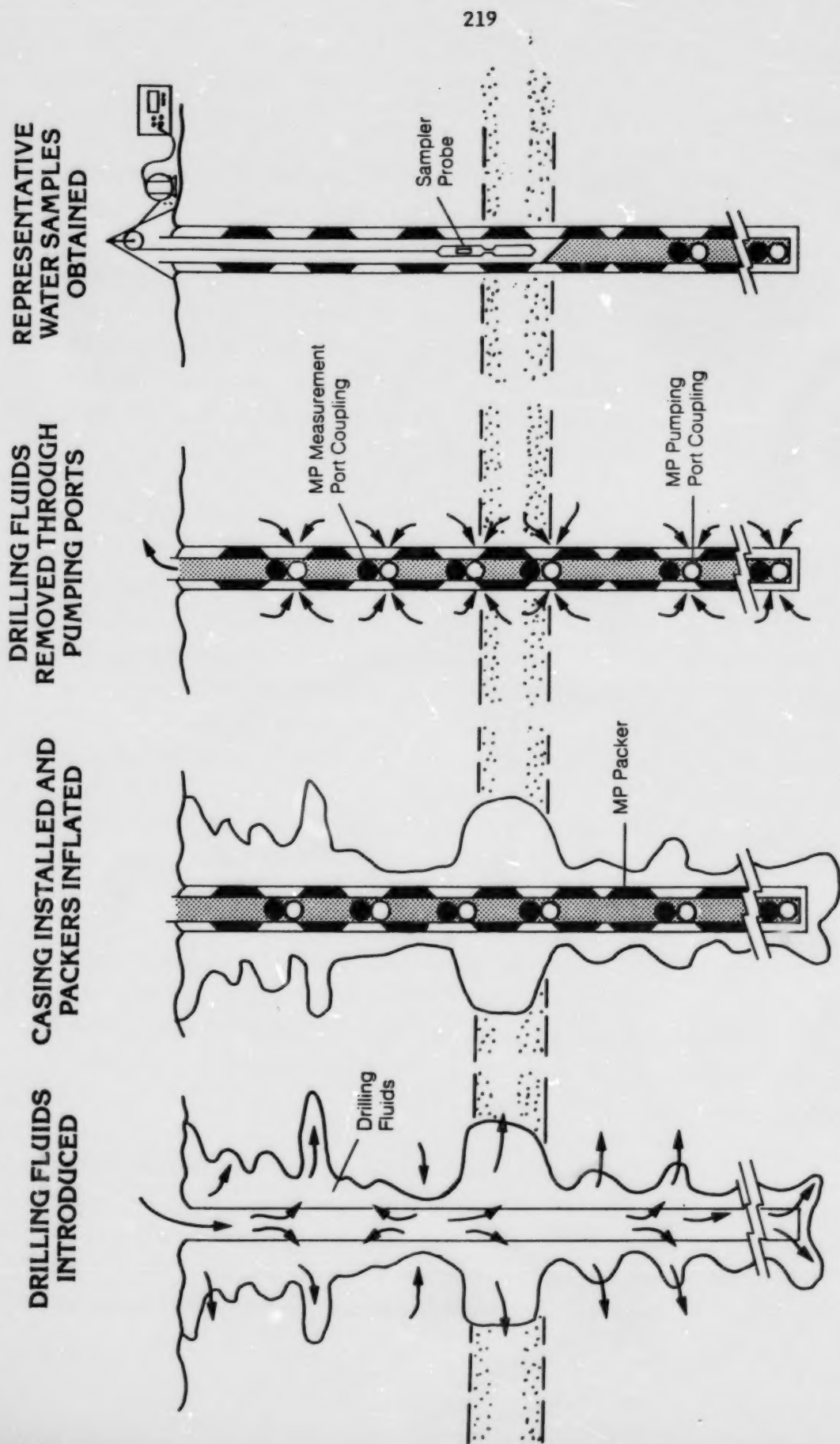


Figure 3.16 Installation and Development with the Westbay System

penetrating the steamed zones of Cretaceous age in the study area. Ongoing testing and development by Westbay has reportedly found that modifications to facilitate operation in excess of 100°C are possible. However, the equipment is in the development stage at present. Also, a substantial increase in cost is incurred in using a system in 100°C versus 60°C conditions (Smith, 1986).

A further limitation of the Westbay system is that the integrity of the entire installation is at risk if one port or coupling fails. For instance, if a port continually leaks into the inner casing, representative fluid samples can no longer be obtained through sampling inside the casing (i.e., through the pressure ports). Furthermore, the pressure profile and solute distribution outside of the casing may be affected by the leak.

(3) Multiple Piezometer Nest System

The multiple piezometer nest system consists of several individual piezometers installed in a single large diameter borehole as shown in Figure 3.17. The individual piezometers are relatively small diameter (i.e., 2 inch) facilitating several piezometers per borehole. The primary advantage of this system is that only one borehole is required, although it is of larger diameter than would normally be used for a single well. The example shown in Figure 3.17 has been installed at the Hanford Site in the State of Washington as described in Jackson and Veatch (1985). Six piezometers of 1.75 inch nominal ID were installed in a 12.25 inch diameter borehole to a maximum depth of 3900 feet. Each individual piezometer is completed in a selected interval using a wire wrapped well screen surrounded by a sand pack. A coarser gradation sand and pea gravel pack overly the sand pack surrounding the screen to prevent erosion during placement of the cement seal.

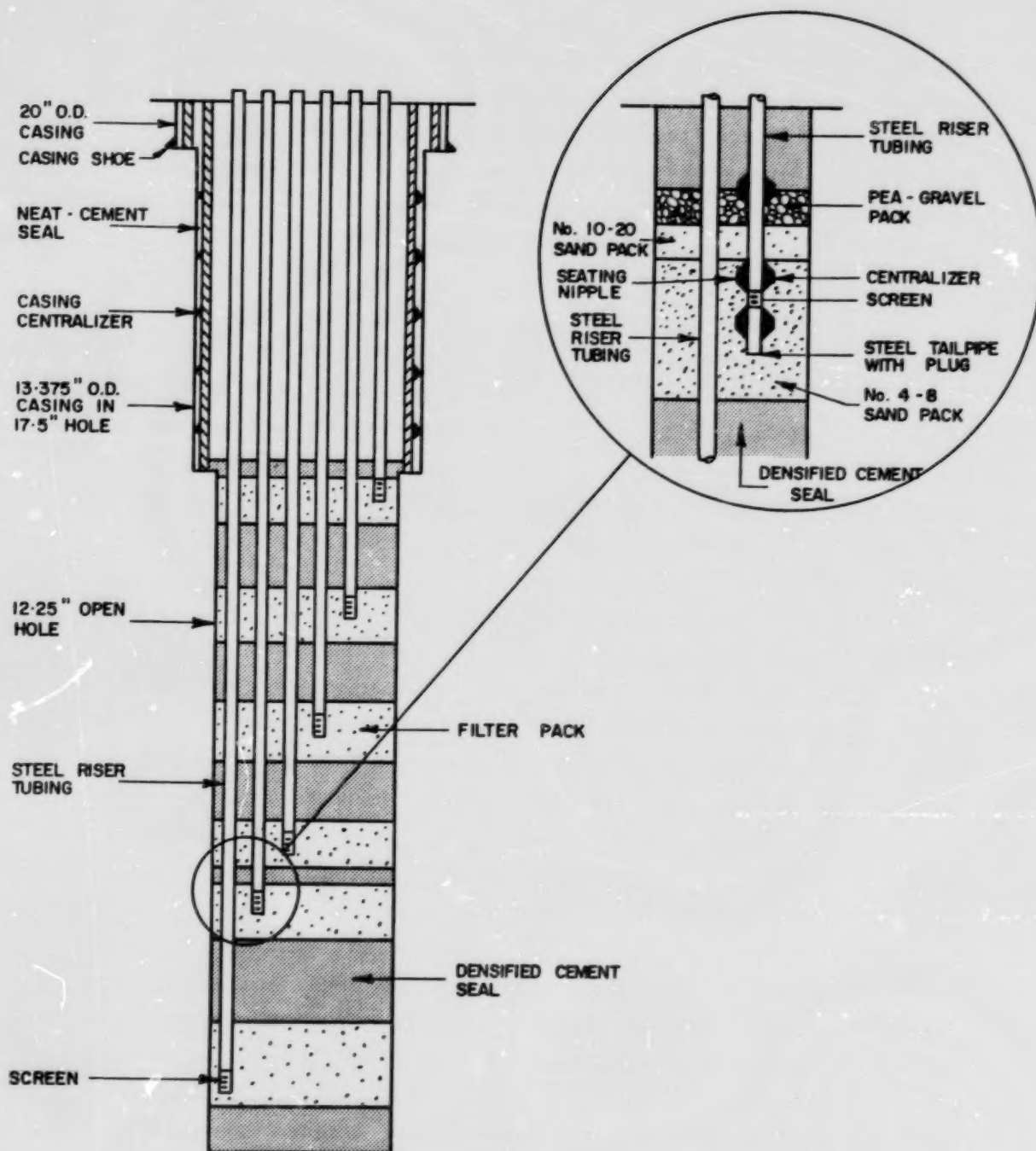


FIGURE 3-17 MULTIPLE PIEZOMETER NEST COMPLETION
(Modified after Jackson and Veatch, 1985)

To install the multiple piezometer nest, a unique installation method is required as adopted from Jackson and Veatch (1985). The individual piezometers are bundled together as they are lowered into a mud filled hole jointly with a working tubing string. Once the entire nest is in place, all mud is washed from the borehole with an attempt to leave the filter cake in place on the borehole wall. If formations are observed to collapse during drilling, it may be necessary to install a temporary large diameter casing. Once the drilling mud is removed, a sand pack is washed into place (through the working tubing string) around the lowermost screen using traced water. Following placement of the sand pack, a cement seal is installed to fill the annulus between the two lowest monitoring intervals (Figure 4). The installation procedure is somewhat time consuming due to the time for curing of the cement seal. This process is repeated for the remaining monitoring intervals and is followed by development of each interval.

One of the key objectives during installation of the piezometer is to remove as much of the foreign material (i.e., drilling mud) from the monitoring interval as possible. This is essential to minimize the adverse impacts on groundwater quality and should be a high priority during piezometer installation. The piezometers would be developed following installation of all six piezometers. Development is performed to remove all traces of drilling mud and to condition the pack materials thus preventing infiltration of fine sediment to the piezometer. Development would involve conventional development techniques such as mechanical surging, bailing, air or water jetting, swabbing or pumping. Development may also involve the use of dispersing agents to aid in removal of drilling mud and mud cake from the formation and pack materials. Alternatively, degradable drilling muds can be used which are more readily removed from the test interval. However, some adverse impacts on groundwater quality may be associated with these muds because of their chemical composition.

One disadvantage of the multiple piezometer nest system is the requirement for a larger diameter borehole. At the Hanford site, a 12.25 inch diameter borehole was used to install six 1.75 inch piezometers. It is expected that a borehole of the same diameter would be required to install six (and possibly more) 5 cm minimal I.D. piezometers. The increased borehole diameter is expected to create a small increase in drilling costs over more typical borehole sizes.

A second disadvantage of the multiple piezometer configuration is that the presence of cement in contact with formation waters will probably have an adverse impact on water quality in the form of elevated pH. In a similar installation, Nakamoto et al. (1986) observed a rise in pH from 7.5 to 12.7 in waters exposed to curing cement. Furthermore, they observed that the pH of water exposed to cement continued to rise above 8.0 following one year of curing and that flushing of the interval did not permanently reduce the occurrence of elevated pH. The effects of cement on water quality sampling can be reduced by a number of means. For instance, by positioning the well intake screen in the center of the sand pack (in the vertical sense), higher pH waters must travel a greater path length of the screen intake. Furthermore, by purging the well prior to sampling, it is probable that most high pH water will be removed or diluted to negligible levels. The kinetics of cement dissolution are likely sufficiently slow that negligible change in pH will occur between the end of purging and the actual sample collection. However, it is recommended that pH be monitored during purging to ensure that stable values exist.

Pressure measurement would best be performed using a packer/transducer system situated immediately above the monitoring zone (Figure 3.13). The packer/transducer would be lowered into place on a strain cable with the packer inflation line and transducer cable bound to it. The packer inflation line would be partially full of water to

prevent collapse with the pressure differential required for inflation provided by pressurized air or gas. The packer would be deflated and the transducer/packer configuration removed to collect water quality samples and allow calibration.

Fluid samples would be collected following removal of the packer/transducer configuration. The well would be purged of several well volumes by swabbing and a sample would be collected using one or more pressurized sample cylinders suspended on a reinforced tube. The sample cylinders would be pressurized during lowering downhole. The borehole fluids would then be sampled by reducing the pressure and allowing fluids to flow into the sample cylinders.

The material used in piezometer construction would most likely be stainless steel in order to enhance the life expectancy of the installation in the corrosive environment at depth. Cement used in isolating the monitoring intervals should be resistant to highly saline solutions. Pack materials should be selected to be compatible with waste and formation fluids. This would likely involve the use of more resistant media such as igneous and metamorphic derived granular materials (i.e., silica).

Of the possible single and multiple borehole completions reviewed, the multiple piezometer nest system is considered to offer the best characteristics from a scientific, operational and cost effective standpoint. It is this completion configuration which is recommended for use in the monitoring and testing program. Also, the multiple piezometer nest system is used in deriving cost estimates in Section 3.7.

3.5 FIELD PROGRAM ALTERNATIVES

Three field program alternatives have been developed which fulfill the objectives of the field testing and monitoring program. These objectives, as derived from the Terms of Reference for this study, are to design a field program to achieve the following:

- Provide the geologic, hydrogeologic and hydrogeochemical data to aid the calibration and verification of the aforementioned theoretical and laboratory information; and
- Address the issue of impact of subsurface waste disposal in the Cold Lake oil sands area.

Through the course of developing the field program alternatives, the objectives have been further refined to incorporate the following points:

- The monitoring program should address both (1) the background conditions in the absence of any effects from, waste fluid injection and (2) the impact of waste fluid injection now and in the future;
- The field program should aim at collecting sufficient information to confirm existing data for the entire stratigraphic sequence above the Precambrian but should concentrate primarily on the waste injection zones and the formations in close proximity to them.

The three different field program alternatives which were developed for this project are:

- Monitoring Program;
- Limited Testing Program;
- Full Scale Testing Program.

These field program alternatives are discussed in the following sections in terms of their relative merits and drawbacks with respect to their ability to fulfill the objectives of the field program. Recommended components of the three program alternatives are outlined in Table 3.17.

The well completion for each of these programs are all the same and consist of the multiple piezometer nest recommended in Section 3.4. Pressure monitoring and water sampling equipment and methodologies are again those discussed in Section 3.4 for the multiple piezometer nest.

In this feasibility study, a specific location(s) has not been selected for the well monitoring system. However, it is expected that the monitoring system would be located in an area of highest preference as identified in the candidate field monitoring locations section (Section 3.2).

With regards to priority for field monitoring system installation, it is recommended that a multiple piezometer nest to assess the impact of waste fluid injection at sites of immediate concern be given highest priority for installation. Of second priority is the installation of a monitoring system to assess background conditions. Subsequent installations should be aimed at identifying the impact of waste injection near to injection sites not already addressed by the initial monitoring installation. That is, at injection sites or areas where the rates are sufficiently high that a concern exists over potential environmental impacts.

Table 3.17 Summary at Field Program Alternatives

Program Component	Monitoring Program	Limited Testing Program	Full Scale Testing Program
Geological Interpretation (from 3.3.1):			
- Drilling Program			•
- Formation Sampling and Borehole Logging			•
- Lithologic Description	o	o	•
- Additional Geologic Studies	o	o	•
- Stratigraphic Interpretation	o	o	•
Geophysical Logging (from 3.3.2):			
- Casing Assessment Only	o		
- Recommended Cased Hole Logs (including casing evaluation)		•	•
- Recommended Uncased Hole Logs		o	
Hydrochemical Sampling Program (from 3.3.3):			
- Drilling Fluid Tracer Program			•
- Sampling During Drilling			•
Hydraulic Testing Program (from 3.3.4):			
- Single Packer Tests During Drilling			•
- Double Packer Tests In Uncased Holes			•
- Double Packer Tests Through Casing Perforations		o	
Long Term Monitoring (from 3.4):			
- Continuous Pressure Monitoring	•	•	•
- Quality Sampling	•	•	•
- Monitoring Facilities Completed in Cased Borehole (6 zones)	•	•	
- Monitoring Facilities Completed in Uncased Borehole (6 zones)	o	o	•

- Recommended components of the monitoring program
- o Options for further consideration which are not included in cost estimates

Prior to proceeding with a detailed discussion of the various program alternatives, the advantages and disadvantages of using either existing or newly drilled boreholes should be discussed. With existing wells, a number of concerns arise regarding the nature of the historical data. The emphasis of a hydrogeological field program is somewhat different than testing performed during drilling operations conducted by the oil industry. Similar parameters are measured in each type of program (i.e., permeability, porosity) yet the measurement techniques may not provide data of sufficient reliability. For example, permeability values in the oil industry are measured on cores using air at ambient pressures. However, with laboratory methods, only the matrix permeability is assessed. The permeability of fracture zones, which is of great interest in a hydrogeology study, is usually not conducted in routine laboratory assessments of permeability as core is usually not recovered or is broken. Thus the bulk permeability of the formation may be somewhat underestimated due to the use of laboratory test methods versus in situ methods.

The objectives of oil industry testing are different than those of a hydrogeological testing program. Oil field testing typically concentrates solely on potential oil or gas reservoirs with very little data collected regarding overlying confining units or non-oil bearing formations at depth. For this reason, very little data exist on non-oil bearing formations. This poses a problem in using existing wells in a hydrogeological program.

It should also be noted that in electing to use existing wells, very little choice exists in well location, core analysis, or geophysical and hydrogeological studies. Most of these decisions would have been made at the time of initial well installation. One or more pertinent studies and/or tests may have been neglected, lost or poorly conducted such that the reliability of the data is in question.

Existing wells are presumably installed for some purpose which may have involved testing which may subsequently compromise the data obtained in a monitoring program. Wells may have been installed as production wells which are often treated to enhance the permeability by either hydrofracturing and/or acidizing. The confidence in the information obtained from these wells would be in question if either of these activities were performed. The permeability of the formation adjacent to and at close radius to the completion interval, which is the zone tested during most single well tests, would be altered from the in situ value. The water chemistry would be different from background levels due to the introduction of drilling fluids, acidizing, foreign materials (i.e., propping agents) and mixing with different formation fluids through the hydrofractured zone. The uncertainties in the history of the borehole such as lost or incomplete records could pose a major problem in the validity of data. Numerous other factors plague the use of existing wells for measuring representative in situ conditions including:

- The use of diesel fluid as a non-corrosive fluid in the borehole annulus;
- Non-thermal cement used around casing in the heavy oil extraction zones;
- Uncertainties in historical well use;
- Mixing of waters between different formations through flow in the casing;
- Introduction of foreign materials to the formation;
- Effects of casing perforations on hydraulic tests.

Although many of these can be minimized through the criteria used for well selection, the fact remains that all parameters are being measured in a disturbed state which will always remain as a contentious point.

3.5.1 Monitoring Program

A monitoring program has been developed based on the use of existing wells. It is assumed that a cased well exists which penetrates to the formation of interest and that the well can be recompleted in a number of intervals of interest. Whether a well of this nature exists or whether or not permission for access can be obtained is unknown (This is also assumed for the limited testing program).

The monitoring program alternative involves solely the collection of water samples for chemical analysis and the monitoring of pressure changes in the completion intervals as outlined in Section 3.4. The recommended components of the monitoring program are summarized in Table 3.17. As is evident in this table, no further geophysical or hydraulic testing is performed beyond that already in existence except for cement bond and cement evaluation logs.

In utilizing an existing borehole, it is likely that a certain amount of testing was performed during initial well installation. Resistivity and spontaneous potential logs are required by ERCB and additional logs may have been performed as seen fit by the oil companies. Geologic logs, core analysis and drill stem tests were also likely performed by the oil company installing the wells. Any existing wells are probably cased and the casing cemented in place with the well annulus open to one or more zones through the casing perforations.

In a long term monitoring program, it is desirable to have a multiple well completion which facilitates pressure measurements and fluid sample collection from a number of stratigraphic horizons. Thus, it will be necessary to perforate the well casing and to install a multiple well completion as discussed in Section 3.4. However, existing wells are likely to be of narrower diameter than the 12.25 inch hole required. For this reason, it is assumed that an eight inch cased hole is used. As a consequence, the design for the multiple piezometer nest completion is modified to use $1\frac{1}{4}$ inch diameter piezometer pipe and screen. No serious difficulties are expected to be encountered using the narrower diameter pipe although it is more desirable to use a minimum of two inch diameter to facilitate pumping and easier operation of testing and monitoring equipment. Furthermore, the presence and corrosion of an existing steel casing outweighs the benefits of stainless steel casing for the individual narrow diameter piezometers. As a consequence, the costs of stainless steel are not justified for the use in a cased well. The lower cost carbon steel is considered to be more in line with the expected quality of the data obtained using an existing steel casing. This applies to both the Monitoring and Limited Testing Programs.

There are a number of adverse implications on water quality in using an existing well which are discussed in Section 3.3.3.

A number of tests should be conducted prior to using existing wells to assess whether the well is in suitable condition for use as a monitoring well. A question of primary concern which needs to be addressed is the condition of the cement seal. This concern should be assessed using a cement bond and cement evaluation logs.

The age and condition of the well casing is another question which arises. In general, it is advisable to avoid older well casings subject to breakdown by corrosion. Failure of the casing may occur due to stressing during installation of monitoring equipment. Heat stress

is also a concern where the casing passes through an active heavy oil extraction zone. For this reason, boreholes with casing greater than approximately five years of age should be avoided.

In some instances, it may be desirable to perform additional studies on available cores or chip samples. This could serve to confirm the existing analysis or to provide additional information. Possibilities are covered under the Lithologic Description, Additional Geologic Studies and Stratigraphic Interpretation components of the Geologic Program (Section 3.3.1). Further studies of this nature are not considered to be part of the Monitoring Program but have been identified as possibilities for further consideration (see Table 3.17).

In utilizing existing wells, it is conceivable that the wells may be drilled deeper to intersect zones of interest. In this case, the testing and monitoring recommendations developed under the full scale testing program should be adopted in performing the in situ assessment. However, this option is not considered further in this feasibility study due to difficulties in assessing the existence and availability of wells for recompletion.

In the unlikely event that existing uncased boreholes are identified for use as a monitoring well, the well completion would differ somewhat but the costs are not expected to vary significantly. An uncased hole offers the opportunity to perform some geophysical and hydraulic testing. This opportunity should not be passed up and consideration of the limited testing program is strongly recommended.

The detailed design of the multiple piezometer nest is described in Section 3.4 and further considerations are discussed under the full scale testing program to follow.

3.5.2 Limited Testing Program

The limited testing program developed, as for the monitoring program, is based on the use of existing cased wells. The main difference in the limited testing program over the monitoring program is that some limited testing is performed in the well to be used. This includes primarily geophysical and hydraulic tests as outlined in Table 3.17.

If existing testing results are inadequate or non-existent, it is possible to perform further testing although the number of applicable tests and their reliability is limited due to the presence of the well casing and the limited number of test zones. In a situation such as this, geophysical logging is likely to be of greatest use to define or confirm parameters of interest. As a minimum, logging performed is aimed at assessing the integrity of the casing and cement. If the cement is relatively intact and the well is selected for use in the field program, then neutron and possibly gamma (natural) and spectrometry logs should be considered as all are applicable for cased holes (the information obtained by performing these logs has been identified in Section 3.3.2).

Hydraulic testing is limited to the stratigraphic zones adjacent to casing perforations. As mentioned in the preceding section, it is desirable to use a multicompletion borehole to perform long term monitoring. Thus, hydraulic testing can be performed through the casing perforations in several zones in each borehole. The question of the effect on hydraulic response of testing through casing perforations has arisen. This is not expected to be a problem provided that casing perforations are fairly frequent and do not limit flow. These tests should consist of straddle packer tests using a packer

spacing which extends over all casing perforations in an interval. The methodology recommended for performing double packer tests is discussed in Section 3.3.4. This methodology is recommended for the hydraulic testing to be performed as part of the limited testing program.

The design of the multiple well completion is discussed in Section 3.4 and further considerations are outlined as part of the full scale testing program.

3.5.3 Full Scale Testing Program

The full scale testing program would involve drilling, testing, sampling and construction of long term monitoring facilities (see Table 3.17). The main advantage of the full scale program is the flexibility to locate the test well(s) at the optimal location and to be able to perform testing and sampling under essentially undisturbed conditions. In this way, the reliability and representativeness of the data are better defined as most of the uncertainties associated with using existing wells (i.e., poor well completions, degraded well casing, etc.) are absent.

In the full scale testing program, hydrogeologic, hydrogeochemical and geophysical testing can be performed in all formations of interest: both aquifers and aquitards can be evaluated. Core samples can be retrieved and analyzed in all formations. Hydraulic testing and pressure measurement can be performed under unperturbed conditions leading to more reliable estimates of these parameters. The optimal suite of geophysical studies can be run which can correlate and guide the hydraulic testing and monitoring program. Geochemical sampling is relatively uncomplicated by either communication with different zones or introduction of foreign materials.

The individual components of the full scale testing program are identified in Table 3.17. It should be noted that a number of assumptions were made regarding the full scale testing program in order to arrive at cost estimates (Section 3.7). As the plans for monitoring system installation evolve, it may be desirable to modify these assumptions to better reflect the needs of the program. However, the assumptions made in this report are considered by INTERA as the best estimate of what would be expected during a full scale field testing program. The components of the full scale testing program are essentially those discussed in Sections 3.5.1 and 3.5.2 plus the following additional requirements.

The geological interpretation involves the components listed in Table 3.17. The drilling program consists of drilling a 17.5 inch diameter hole into the top of the Colorado Group, installing surface casing and continuing to approximately 1300 m depth using a 12.25 inch diameter drill bit. Cores would be collected over approximately 25% of the pre-Cretaceous stratigraphy (i.e., 300 m) with the following formations tentatively identified for coring:

- Colorado Group
- Upper Mannville Group
- Clearwater Shale
- Lower Mannville Group
- CBWA
- Prairie Formation
- Keg River/Methy/Winnipegosis Formation
- Contact Rapids
- Cold Lake Formation
- Ernestina Lake Formation
- Basal Red Beds
- Cambrian/Granite Wash

Cores retrieved from these formations should be analyzed using API (1960) "Recommended Practice for Core-Analysis Procedure" to obtain horizontal permeabilities, porosities and densities. Further detailed core analyses are not considered necessary at this time but may be considered at a future date particularly to assess directional permeabilities.

A mud program which is based on a salt saturated drilling mud is recommended. This mud is utilized to inhibit dissolution of evaporite beds of Upper and Middle Devonian age. However, it is also recommended that natural muds be used during drilling of the surface hole to minimize contamination of potable groundwater supplies.

The full scale testing program will require a full size rig to remain on site from the start of drilling until such time as the monitoring system is installed and completed. It is not considered worthwhile to move a smaller rig onto the well following drilling as the working capabilities of a full size rig are considered necessary for the well completion task and mobilization costs for a workover or service rig would add to the project cost.

Twelve samples of geologic media should be selected for additional geologic studies as discussed in Section 3.3.1. The formations from which samples would be selected are the same as for coring listed previously. The studies to be performed include x-ray diffraction, thin section studies, grain size analysis, cation exchange capacity and carbonate content.

The geophysical logs to be performed as outlined in Table 3.6, are aimed at assessing the lithologic and hydraulic properties through correlation to the logging response. All geophysical surveys, would be performed throughout the entire depth of the borehole.

The lithologic description and stratigraphic interpretation would be performed by a site geologist who is on site for the duration of the drilling and testing program.

A dual drill fluid tracer (see Section 3.3.3.2) should be used during drilling to assist in obtaining representative formation fluid samples. On site analysis of the traced drill fluid would be performed using a high pressure liquid chromatograph and specific ion electrodes or equivalent. Tracer concentrations would be maintained at constant values in the drill fluid and would be checked periodically to ensure compliance. During sampling operations, the second tracer would be monitored frequently to guide the purging operation. M-TFMB would be analyzed when concentrations drop to low levels in order to more accurately quantify the amount of tracer remaining.

Formation fluid samples collected during drilling should be considered as "grab" samples and suitable for inorganic analysis or screening tests only. Organic samples collected in completed wells as part of all three programs should be initially analyzed by screening tests, such as those given in Table 3.18. The result of the screening tests can be used to define suitable organic indicators, such as those listed in Table 3.18. Inorganic samples can be analyzed for the full suite of inorganic contaminants given in Table 3.14 or the inorganic indicator parameters (Table 3.18) depending on the purpose of the sampling.

All fluid samples would be collected using a pressurized sample cylinder as discussed in Section 3.3.3. Fluid samples would be collected adjacent to the zone of interest in both cased and uncased hole applications. Sampler volume is generally sufficient to analyze for indicator parameters (i.e., 2 litres). Additional fluid volumes would be collected if additional parameters are to be assessed (i.e., contaminants listed in Table 3.14).

Table 3.18 Screening Tests and Possible Indicator Parameters

Screening Tests

Total Aromatic Hydrocarbons
Total Chromatographable Organics
Total Organic Carbon
Total Phenols
Total Volatile Organics

Inorganic Indicator Parameters

Alkalinity
pH
Temperature
Electrical Conductivity
Major Ions (Ca, Mg, SO₄, HCO₃, Cl, Si, Cl, F, Na,
H₂CO₃, B, Fe, NO₃, K, Sr)

Organic Indicator Parameters

TOC
Phenols
Oil and Grease
Naphthalene
Benzene
Quinoline
Methylaniline

In the hydraulic testing program, single packer tests would be performed in the higher relative permeability zones during drilling. The following formations are targeted for single packer tests:

Viking Sandstone
Upper Mannville Group
Lower Mannville Group
Pre-Cretaceous Unconformity
CBWA
Keg River/Methy/Winnipegosis
Contact Rapids
Ernestina
Basal Red Beds
Cambrian/Granite Wash

It is expected that pressure measurements in these zones will provide a representative indication of the pressure profile along the borehole.

Further hydraulic testing, to be performed following drilling and geophysical logging, would involve testing of lower permeability zones where the pressure response is expected to be relatively long. Also, previously tested zones may be retested. Target zones include:

Colorado Group - Labiche Formation
 - Joli Fou Formation
Clearwater Formation
Ireton Formation (if present)
Prairie Evaporite - 2 tests
Cold Lake Formation
Lotsberg Formation

Hydraulic testing in these zones should provide an indication of the largely unknown hydraulic properties of the lower permeability or confining units.

In terms of well completion, a 10 m long stainless steel well screen would be centered in a 30 m long sand packed interval and attached to a 50 mm internal diameter premium flush jointed stainless steel pipe or casing to surface. Thermal cement should be used to fill the annulus in all zones including and above the Lower Mannville Group while Class "G" cement will be utilized below. A surface casing of 340 mm (13.375") should be installed to approximately 200 m below surface into the top of the Colorado Group.

Following installation of the multiple piezometer system, each piezometer would be developed using swabbing to remove drilling mud and foreign fluids from the test interval. The drill water tracer concentration would be monitored during this operation to determine when foreign fluids have been removed from the interval. Fluid samples would be collected once tracer concentrations become negligible. Samples would be collected and analyzed for screening tests or the full suite of parameters (Table 3.14) at this time followed by ongoing sampling and analysis for indicator parameters (Table 3.18).

To monitor pressure, pressure transmitters will be positioned below inflatable packers following water quality sampling. The transmitter and packer will be suspended on a wireline adjacent to the completed zone in each of the six piezometers. The packer inflation line and transmitter cable will be attached to the strain cable or wireline which is lowered and raised using a cable reel.

3.6 MONITORING PROGRAM ADMINISTRATION

3.6.1 Management Control Strategy

Management control strategies are useful in establishing the organizational framework through which the project participants can interact. The organizational framework provides pathways for information exchange between the various participants. In this feasibility study, organization charts have been adopted to illustrate the relationship between project participants and in illustrating their relative responsibilities. Management control strategies have been developed for both the testing and long term monitoring programs.

The project management strategy for the field testing program is illustrated in Figure 3.18. This organizational strategy was developed such that either a private or public sector group may be ultimately responsible for project management. The project management group is lead by a project manager who is responsible for communication between all parties involved in the monitoring and testing program. The sponsoring group may involve provincial, federal, scientific community or industrial representatives. The project manager is also responsible for communication with the field supervisor.

The field supervisor is responsible for overseeing all drill site activities, supervising site personnel, coordinating subcontractors and managing the day-to-day events in the field. The field supervisor would report daily to the project manager on matters related to project progress, delays in scheduling and subcontracting issues. Weekly progress reports would be submitted by the field supervisor documenting the use of materials, progress in drilling, summaries of tests performed and revised and updated schedules.

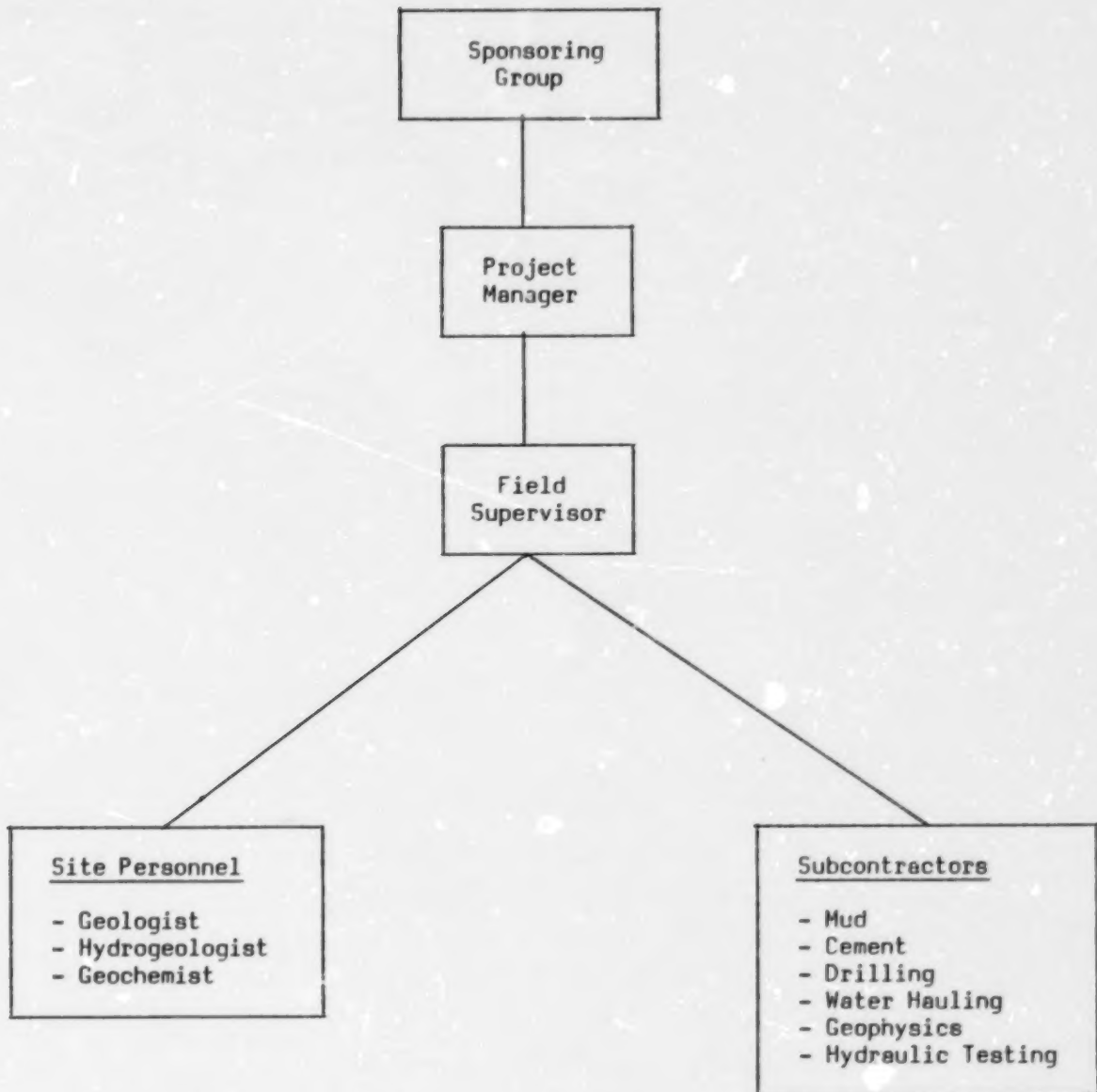


Figure 3.18 Organization Chart for Testing Program

The site personnel would consist of a geologist, hydrogeologist and geochemist. The involvement of these personnel is required at different stages in the testing program and would not necessarily be present throughout the entire program period. The site geologist would be responsible for overseeing coring operations, logging drill cuttings, lithologic descriptions and stratigraphic interpretations. The geologist would work together with the hydrogeologist in selecting zones for pressure measurement/hydraulic testing and interpretation of geophysical logs leading to selection of completion intervals.

The site hydrogeologist would be involved in overseeing the hydraulic testing program. This involves selection of zones to test using both single packer tests during drilling and multiple packer tests conducted subsequent to drilling operations. The site hydrogeologist would be involved in assisting the hydraulic testing subcontractor, the geochemical sampling and in onsite interpretation of test results. Duties would also include selection of completion zones through liaison with the site geologist and geochemist.

The site geochemist would be involved in overseeing the drill water tracer program and performing sampling and analysis of formation fluids. The drill fluid must be periodically sampled to ensure a constant tracer concentration and additional tracer must be added when the volume of drilling fluid is increased. During sampling, the fluids yielded by the test interval are monitored until the drill water tracer drops to low or negligible concentrations. At this point, samples are collected and shipped to a laboratory for analysis.

Many of the tasks performed at the drill site would be subcontracted to companies specializing in a particular area or skill. The subcontractors typically include drilling, mud, cementing, water hauling, geophysical logging and hydraulic testing. Liaison with and

coordination of subcontractors is the field supervisors duty although many of the subcontractors may work quite closely with the site personnel (i.e., geologist, hydrogeologist, geochemist).

The organizational relationships illustrated in Figure 3.18 developed primarily for a full scale testing program. However, essentially the same overall organization would also be utilized in either the limited testing or monitoring programs outlined in Section 3.5. The main difference would be that the drilling related tasks would not be included. Such tasks include drilling and mud subcontractors activities.

An organizational framework has also been developed for the long term monitoring program. This framework, as illustrated in Figure 3.19, serves to depict the various organizations who may be involved and how they interrelate. The organizational framework centers around the project coordinator. The project coordinator would most likely be a designated person within the organization charged with responsibility for the monitoring activities. This organization would probably be a government group but a private sector group is not necessarily ruled out. The project coordinator would be responsible for liaison with interested parties such as those listed in Figure 3.19. The project coordinator would also be responsible for reporting the status of the monitoring program to the scientific advisory group and in ensuring implementation of recommendations of the scientific advisory group. The project coordinator would also directly oversee the work performed in the field by the field technicians group. This would involve ensuring that quality assurance and quality control guidelines are adhered to, that minimal data loss is occurring and that data obtained are representative of in situ conditions.

The Scientific Advisory Group would consist of experts in the area of groundwater monitoring technology, waste fluid injection, contaminant transport and analytical chemistry. The group would be

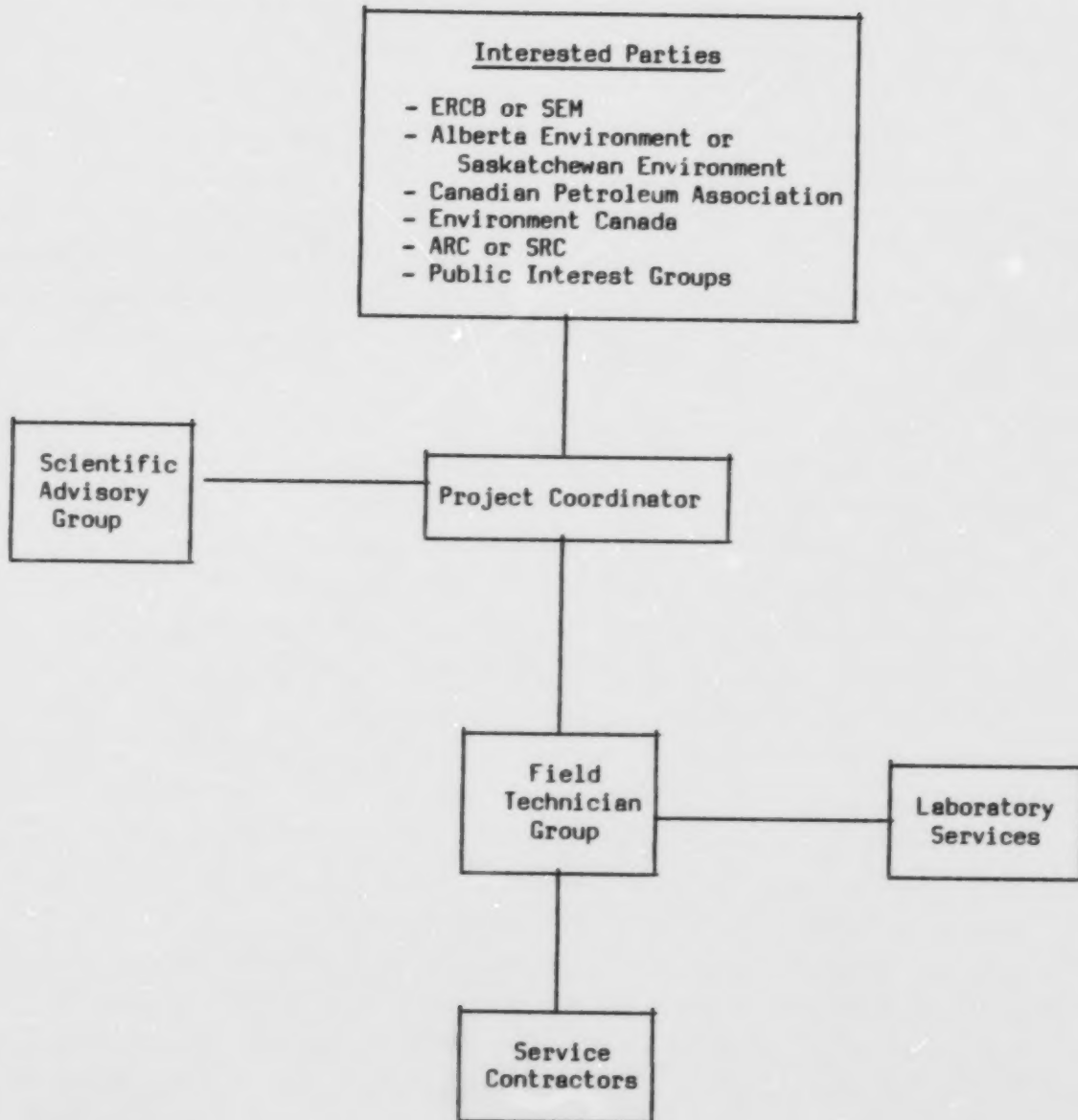


Figure 3.19 Organization Chart for Monitoring Program

responsible for reviewing the monitoring program activities and making recommendations aimed at ensuring the reliability and representativeness of the field data.

The Field Technicians Group would be responsible for day-to-day data collection and equipment maintenance tasks. Duties would include transducer calibration and pressure monitoring as well as all activities associated with collection of groundwater samples. The group would be responsible for submitting fluid samples to the project laboratory, liaison with the laboratory, data processing and preliminary screening of analytical results. The group would also coordinate other parties involved with testing and monitoring activities (i.e., workover rig for swabbing of piezometers).

3.6.2 Scheduling

Schedules have been prepared for each of the three field program alternatives, as follows:

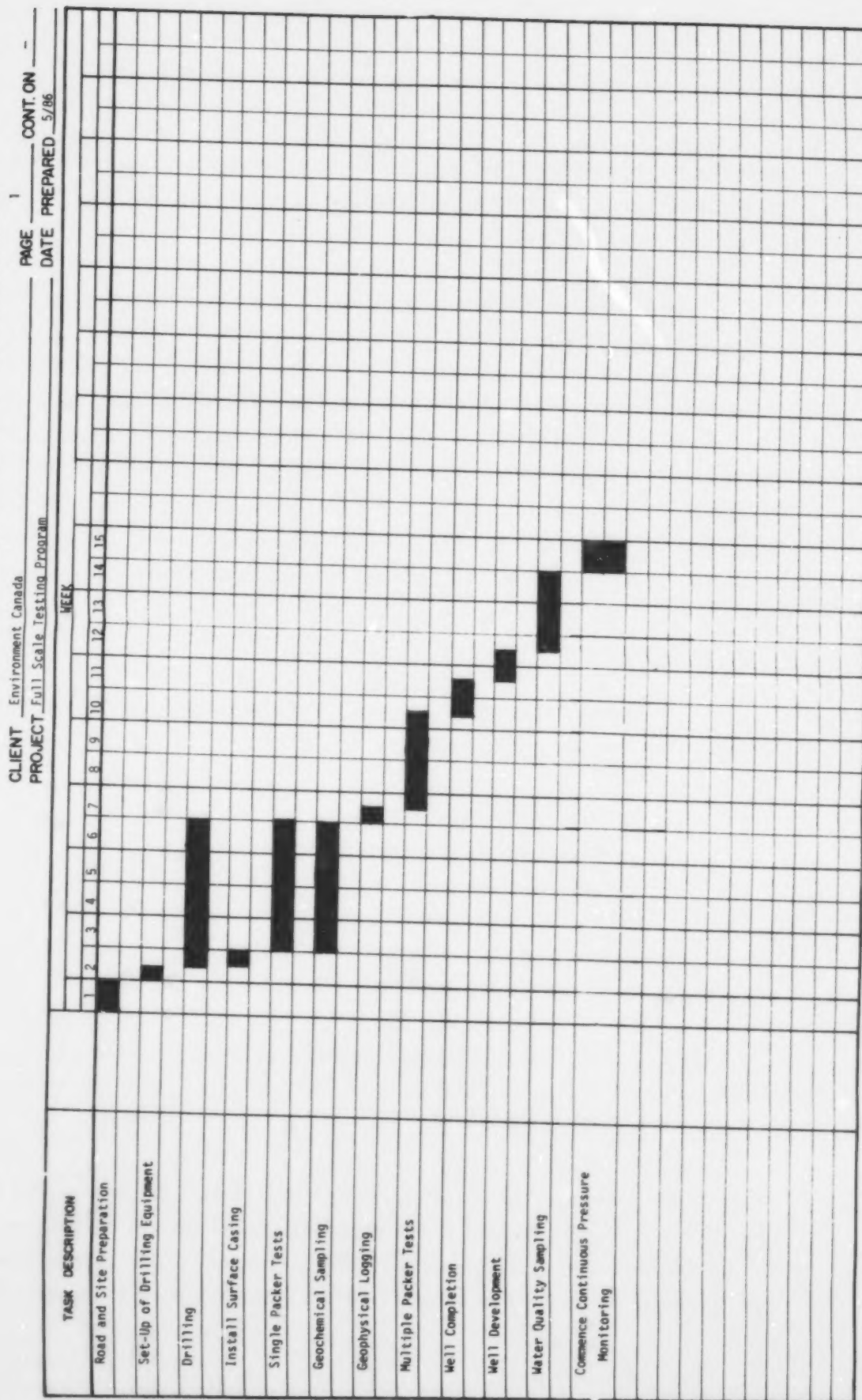
- Full Scale Testing Program;
- Limited Testing Program;
- Monitoring Program.

All schedules are based on installation of one multiple piezometer nest as described in Sections 3.4.1 and 3.5.3. The installation of a piezometer nest is a continuous operation from start to finish and can not be phased over several fiscal years. However, additional piezometer nests at other locations can be installed independently as required.

A schedule has been developed for the full scale testing program to include all activities commencing with site preparation up to the commencement of pressure monitoring (Figure 3.20). The schedule was developed based on estimated times for completion of the individual

Figure 3.20 Schedule for the Full Scale Testing Program

PROGRAM SCHEDULE AND MANPOWER ASSIGNMENT



tasks. However, due to a number of uncertainties associated with the full scale testing program, it is difficult to accurately estimate the duration for each task. A task of more certain duration which is critical in scheduling includes drilling of the borehole which is expected to take approximately nine days with continuous drilling. Areas of greatest uncertainty are the geochemical sampling, multiple packer testing, well completion and water quality sampling tasks. The uncertainty in the duration of the geochemical and water quality sampling tasks arises in that the test intervals need to be pumped or evacuated until such time as the concentration of the drill water tracer becomes negligible. The volume of fluid to be evacuated is dependent on the volume introduced which is a function of the number of high permeability zones, the mud design and the duration the borehole is open, all of which are difficult to assess at this time.

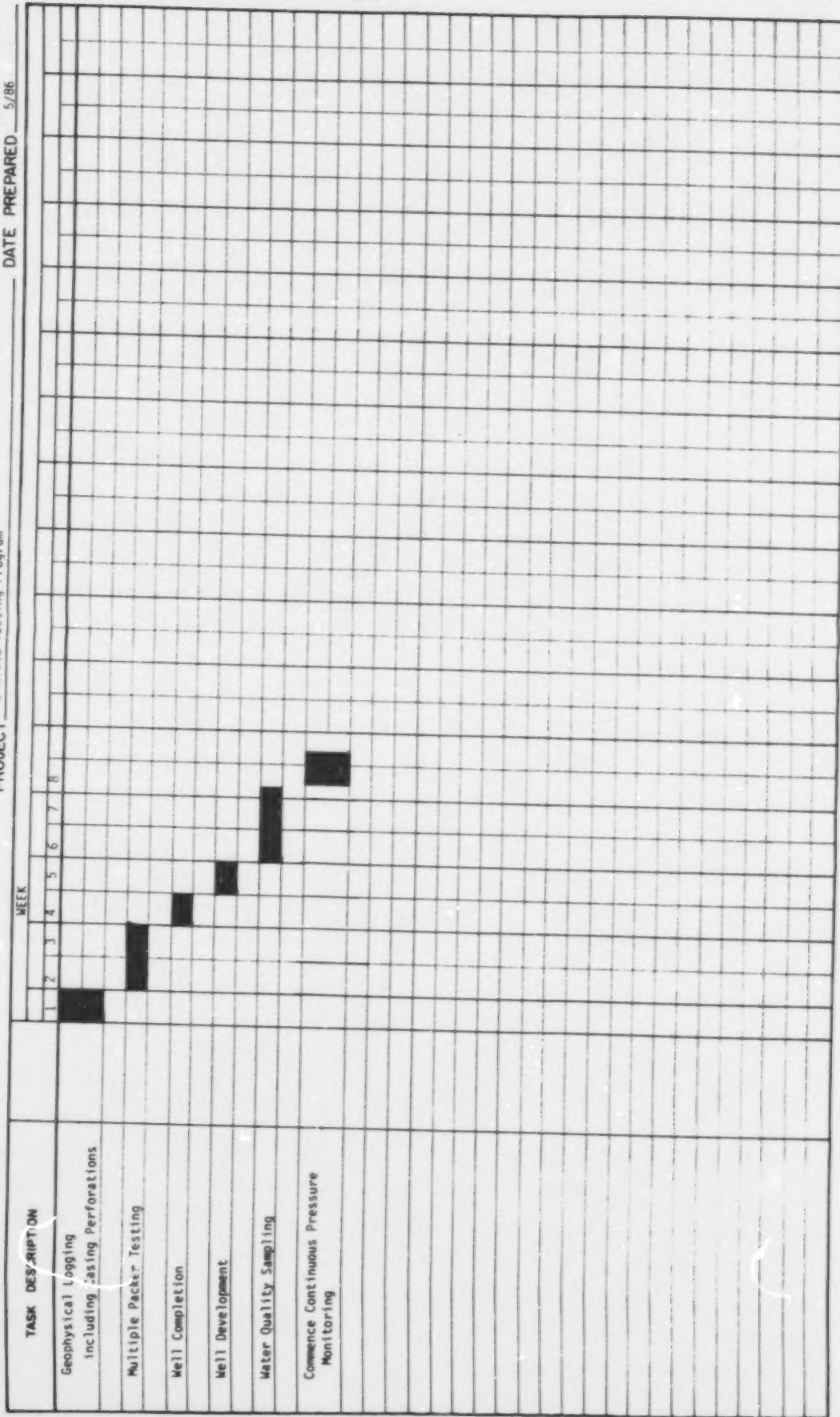
In most instances of sampling in the higher permeability zones, it is expected that removal of traced water would be achieved in approximately one day. In practice, this time would probably vary although one day is considered a reasonable sampling time and has been adopted in scheduling geochemical sampling during drilling. A sampling duration of two days for any one zone has tentively been adopted as an upper limit at which point samples would be collected regardless of drill water tracer concentration.

In the post well installation water quality sampling program, an emphasis is placed on ensuring that representative fluid samples are obtained for chemical analysis as in Table 3.18. Sampling intervals in the completed piezometers are to be developed until drill water tracer concentrations are zero or negligible. Purging and evacuation may require somewhat greater time than sampling during drilling, particularly in the lower permeability confining units. The duration of sampling in each of these intervals is estimated at three days per zone. This is reflected in scheduling of the water quality sampling task in Figure 3.21 to 3.22 of the Limiting Testing and Monitoring Programs, respectively.

Figure 3.21 Schedule for the Limited Testing Program

PROGRAM SCHEDULE AND MANPOWER ASSIGNMENT

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The uncertainty in the multiple packer tests is related to the dependence of test duration on the permeability of the test interval. In performing single packer tests during drilling, testing is concentrated in the highly permeable zones which are expected to respond relatively quickly. Single packer tests are scheduled at a half to one day per test to account for testing as well as running in and out of the borehole. In multiple packer tests, the purpose is to provide an opportunity to assess the hydraulic properties of lower permeability zones which require a longer period to respond. Lower permeability zones, such as aquitards are generally tested after drilling of the entire borehole is completed in order to allow for a longer testing time, if necessary. After drilling, hydraulic testing can be completed more economically in a continuous logging method. The hydraulic properties of the alleged aquitards are largely unknown at present and need be addressed as part of the hydraulic testing program. Yet, the duration of testing can not be accurately determined at present. Previous experience in testing of very low permeability media suggests that an average test time of approximately one day (Figure 3.20 - 3.22) is realistic in terms of achieving sufficient formation response. Again, this value would vary with the test interval and an upper ceiling of two days is suggested at which point the testing would be curtailed. It should be noted that the duration of multiple packer tests is less for the Monitoring Program and Limited Testing Program as only six zones are tested as opposed to 10 zones in the Full Scale Testing Program.

The duration of well completion is first affected by the time to assemble and lower the piezometer nest into place. Flushing of drilling mud, placement of sand packs and cement followed by set-up time for the cement also affect the duration of this task. One time consuming problem is the potential collapse of the formation subsequent to flushing. The potential for caving is largely unknown at this time. If caving becomes a problem, a temporary large diameter casing can be used as the alternating cement and sand layers are installed. However, this represents an additional amount of time which is not accounted for in the current schedule. Completion of the monitoring wells is expected to take approximately one week.

The schedules for the Limited Testing and Monitoring Programs are somewhat less complex than the Full Scale Testing Program but are subject to the same uncertainties for the multiple packer testing and water quality sampling tasks as discussed previously. The time involved in the multiple packer testing is of a lesser duration in these two programs due to testing in only the six perforated zones for the well completion.

3.6.3 Regulatory Approval

The regulatory requirements for drilling and installation of a monitoring system to perform strictly monitoring and testing of formation fluids are largely non-existent. No specific guidelines or requirements exist. Application for installation of a monitoring system would likely be considered as a special case to be dealt within the broad framework of existing Provincial legislation developed for other situations. The objectives of the monitoring system and the design and installation technique make it difficult to assess what information will be required for regulatory purposes. However, the main regulatory bodies involved can be identified at this time.

In Alberta, formal application to drill a well must be made to the ERCB who administer regulations pertaining to site selection, well design, construction and operation. It is also expected that Alberta Environment would be involved in reviewing and approving the well construction as part of their mandate to ensure environmental protection. It is possible that an environmental impact assessment may be required although no adverse environmental impacts are anticipated. Alberta Environment will also be involved in approving the source of water supply for drilling operations. The Department of Energy and Natural Resources (DENR) may also have some involvement in approval of the well construction although this organization is primarily involved in surface activities related to land clearing and management.

In Saskatchewan, application for well construction must be made to the Saskatchewan Department of Energy and Mines (SEM) who is the government body charged with this responsibility. Saskatchewan Environment is also likely to be involved in reviewing and commenting on possible environmental impacts from the construction of the proposed well.

Regulatory requirements which are certain to be invoked include the requirements for surface casing and restrictions on the use of either oil or salt saturated mud. Surface casing requirements in Alberta generally require cementing of surface casing to 25 m below unconsolidated sand and gravel or 10% of the total well depth. In the study area, sand and gravel aquifers used as potable water supplies are encountered just above the Colorado Shales at approximately 170 m depth in the vicinity of Cold Lake. The ERCB also has the authority to invoke site specific requirements at their discretion. Similar requirements exist in Saskatchewan with SEM. When drilling through evaporite deposits such as the Prairie Formation which may be subject to dissolution, either oil or salt saturated muds are required. Furthermore, brine saturated cement is required in the well completion.

3.7 FIELD PROGRAM COSTS

A comprehensive cost estimate has been prepared for each of the three field program alternatives outlined in Section 3.5. The cost estimates are Level C and are intended to be a level of accuracy sufficient for budgeting purposes. It should be noted that the unique nature of the field testing and monitoring programs recommended in this study has provided some difficulty in estimating costs. The main difficulty is the uncertainty in testing and installation time required to obtain representative fluid samples and to construct monitoring facilities. The primary impact of these uncertainties is in the cost of drilling services which are a major portion of the overall project cost, particularly for the full scale testing program. The time and cost estimates for the proposed program have been derived through consultation with industry and in-house experts and are considered to provide realistic estimates of the costs which may be incurred through implementation of the proposed program.

It should be noted that the unique nature of the drilling, testing and well completion program together with the requirement for only Level C cost estimates has prevented completion of the Canadian Association of Oilwell Drilling Contractors (CAODC) Bid Sheet for Well Specifications for Standard Daywork Contract. The CAODC Bid Sheet is a detailed breakdown of drilling and testing related costs which is much more detailed than the required Level C cost estimates. Level C cost estimates are, according to Department of Supply and Services (Boyle, 1986), of sufficient detail to facilitate budget preparations. As a consequence, the bid sheet has not been completed.

The costs for each of the field program alternatives are itemized in the following pages to agree with the various components of the three programs outlined in Table 3.17. The costs are considered as average costs obtained, where possible, from the reliable industrial sources listed in Appendix D. The assumptions used in arriving at the

cost estimates are stated for each component as well as the source of the costing information. Specific cost items are further itemized where deemed necessary. A cost summary for all programs has been prepared as shown in Table 3.19.

Table 3.19 Cost Estimate

Component	Monitoring Program (\$)	Limited Testing Program (\$)	Full Scale Testing Program (\$)
Geologic Interpretation	0	0	486,400
Geophysical Logging	0	81,400	36,200
Hydrochemical Sampling	0	0	63,800
Hydraulic Testing	0	8,500	43,700
Long Term Monitoring	212,300	212,300	474,700
Engineering Services	19,100	27,200	99,400
TOTAL (\$)	231,400	329,400	1,204,200

COST SUMMARYGeological Interpretation:

● Drilling Program

(a) Core Analysis

- Assumptions: (i) Approximately 25% of the stratigraphy is cored below the bottom of the Quaternary - total = 300 m;
- (ii) Cores are analyzed for horizontal permeability, porosity and density;
- (iii) 0.3 m long cores of 1½" diameter are analyzed.

Core analysis: \$12,500

Source: Core Laboratories

(b) Coring

- Assumptions: (i) Cores are obtained in 10 different zones;
- (ii) Coring is estimated to take 4 days total; The additional drilling rig cost is reflected in the Drilling Program cost estimates;
- (iii) Approximately 25% of the stratigraphy is cored below the bottom of the Quaternary - total = 300 m.

Coring Services: \$17,000

Source: Sedco Drilling

(c) Drilling Mud

Assumptions: (i) Saturated salt mud;
 (ii) Low fluid loss from borehole;
 (iii) Typical drilling conditions for Cold Lake area.

Drilling mud and associated services: \$40,000

Source: Milchem Canada Ltd.

(d) Drilling Services - Monitoring Program

Assumptions: (i) Drilling service costs are those arising from the installation of monitoring facilities and development of completion intervals.

Mob/Demobilization \$ 5,000

Rental Charge 21,000
 \$26,000

Source: Northeastern, Westburne

- Limited Testing Program

Assumptions: (i) Same as for Monitoring Program plus rig time associated with additional testing.

Mob/Demobilization \$ 5,000
 Rental Charge 63,000
 \$68,000

Source: Northeastern, Westburne

- Full Scale Testing Program

- Assumptions: (i) 17.5" diameter surface hole;
 (ii) 12.25" drill hole;
 (iii) Full rental charge during drilling;
 (iv) Standby with crew for duration of testing
 up to completion of water quality
 sampling;
 (v) Costs include expendible drilling
 materials (i.e., bits).

Mob/Demobilization	\$ 18,000
Full Rental Charge	186,000
Standby Charge	<u>125,000</u>
	\$329,000

Source: Northeastern, Westburne

(e) Road and Site Preparation

- Assumptions: (i) Preparation requirements will be
 equivalent to an average oil or gas well;
 (ii) Only applies to Full Scale Testing
 Program.

Road and site preparation: \$7,500

Source: Petroleum Services Association of Canada

(f) Camp Costs - Monitoring Program	\$10,000
- Limited Testing Program	\$30,000
- Full Scale Testing Program	\$50,000

Source: Estimated based on Sedco costs

- Additional Geologic Studies

Assumptions: Twelve samples analyzed in greater detail under the additional geologic studies program.

X-Ray Diffraction	\$3,300
Thin Section Studies	2,400
Grain Size Analysis	600
Cation Exchange Capacity	1,440
Carbonate Content	<u>120</u>
	\$7,860

Source: Geotech, Bondar Clegg

- Lithologic Description and Stratigraphic Interpretation

Assumptions: (i) Tasks are labour intensive and are performed by a drill site geologist on site for the duration of the drilling and testing programs.

Site geologist: \$22,500

Geophysical Logging:

- Casing Evaluation

Assumptions: (i) Cement Bond Tool (CBT) and Cement Evaluation Tool (CET) run over 1300 m depth;

(ii) Perforations include 6 intervals of 10 m in length using 13 shots/metre.

Service Charge	\$ 910
Cement Bond Tool	11,200
Cement Evaluation Tool	10,400
Perforations	<u>28,650</u>

\$51,160

Source: Schlumberger Canada/Alaska

● Cased Hole Logs

- Assumptions: (i) Same as for Casing Evaluation;
(ii) Compensated Neutron Log run over 1300 m.

Service	\$ 910
Compensated Neutron Log	13,515
Full Waveform Log	16,500
Cement Bond Tool	11,200
Cement Evaluation Tool	10,400
Perforations	<u>28,650</u>

\$81,175

Source: Schlumberger Canada/Alaska

● Uncased Hole Logs

- Assumptions: (i) Compensated Neutron Log, Dual Induction,
Density and Full Waveform Logs run over
1300 m.

Service Charge	\$ 910
Compensated Neutron Log	13,515
Dual Induction Log	5,200
Density Log	114
Full Waveform Log	<u>16,500</u>

\$36,239

Source: Schlumberger Canada/Alaska

Hydrochemical Sampling Program:

• Drilling Fluid Tracer Program

(a) Tracer

Assumptions: (i) 10 mg/L tracer achieved in volume =
5 x well volume.

m-TFMB	\$9,330
Second Tracer	1,000
Mixing and metering hardware	<u>1,000</u>

\$11,330

Source: Fisher Scientific

(b) Analytical Equipment

Assumptions: (i) High Pressure Liquid Chromatograph (HPLC)
leased and operated on site for duration
of drilling and sampling up to start of
long term pressure monitoring.

HPLC	\$10,000
Specific ion electrodes or equivalent	<u>2,000</u>

\$12,000

Source: Hewlett-Packard (Note: Estimated from
purchase price)

(c) Chemist

Assumptions: (i) Involved in drill water tracer program and
sampling during drilling.

Chemist: \$10,000

● Sampling During Drilling

(a) Analytical Costs

Assumptions: (i) Fluid samples to be collected from 10
zones during drilling;
(ii) Samples collected during drilling to be
analyzed for indicator parameters;
(iii) Includes duplicates, replicates and
blanks.

20 analysis @ \$425/sample \$8,500

Source: Barringer-Magenta, Zenon

(b) Sampling

Assumptions: (i) Sampling equipment is the same as that
used for the Long Term Monitoring Program
and is covered in that section;

- (ii) Samples are to be collected from 10 zones which is assumed to take 2 days each for tracer concentration to drop to negligible concentrations. This is reflected in the drill rig rental costs.

Sample cylinders (50)	\$20,000
Expendibles (i.e., swab cups, nitrogen gas)	<u>2,000</u>
	\$22,000

Hydraulic Testing Program:

• Single Packer Tests

- Assumptions: (i) 10 tests performed primarily in permeable zones;
 (ii) Testing equipment and technician required for 1 day for each test;
 (iii) Mobilization from Lloydminster.

Hydraulic testing equipment with operator	\$24,450
Mobilization	1,500
Expendibles (i.e., packers)	<u>2,000</u>
	\$28,950

Source: Lynes

● Multiple Packer Tests in Uncased Hole

- Assumptions: (i) 10 zones tested;
 (ii) 1 day/test zone;
 (iii) Tests performed sequentially;
 (iv) Mobilization from Lloydminster.

Hydraulic testing equipment with operator	\$11,600
Mobilization	120
Expendibles	<u>3,000</u>
	\$14,720

Source: Lynes

● Multiple Packer Tests in Cased Hole

- Assumptions: (i) 6 zones tested;
 (ii) 15 hour test;
 (iii) Tests performed sequentially;
 (iv) Mobilization from Lloydminster.

Hydraulic testing equipment with operator	\$6,545
Mobilization	120
Expendibles	<u>1,800</u>
	\$8,465

Source: Lynes

Long Term Monitoring:

- Monitoring Facilities - Monitoring Program and Limited Testing Program

(a) Cementing and Sand Pack - Multiple Piezometer

- Assumptions:
- (i) 6 sand pack zones of 30 m length;
 - (ii) 8" diameter cased hole;
 - (iii) Thermal 3F cement to 580 m (bottom of Mannville) and class "G" cement below;
 - (iv) Mobilization from Lloydminster;
 - (v) Total depth of hole = 1340 m

Cementing service to 1340 m	\$39,500
including blending, delivery,	
sand pack material and travel	

Source: Nowsco Well Services

(b) Well Screen

- Assumptions:
- (i) 6 lengths of 10 m long screen;
 - (ii) 30 m additional for flexibility in well completion;
 - (iii) 1½" diameter wire wrapped screen.

Well Screen	\$10,900
Delivery	<u>1,100</u>
	\$12,000

Source: Hoskin Scientific

(c) Pipe

- Assumptions: (i) 1½" I.D. carbon steel pipe;
 (ii) 4500 m total length.

Pipe	\$22,600
Delivery	<u>2,300</u>
	\$24,900

Source: Zagerman Ltd.

(d) Development

- (i) Consists primarily of additional drill rig time for which 5 days is assumed and has been incorporated into the Drilling Program.

• Monitoring Facilities - Full Scale Testing Program

(a) Cementing and Sand Pack - Multiple Piezometer

- Assumptions: (i) 6 sand pack zones each of 30 m length;
 (ii) 12.25" diameter drill hole (13.375" surface casing);
 (iii) Surface casing to 200 m;
 (iv) Thermal 3F cement to 580 m (bottom of Mannville) and class "G" cement below;
 (v) Mobilization from Lloydminster;
 (vi) Total depth of hole = 1340 m.

Cement service to 1340	\$ 8,560
Class "G" cement	22,623
Thermal 3F cement	24,585
Blending and delivery	22,875
Sand	13,433
Travel	<u>608</u>
	\$92,684

Source: Nowsco Well Services

(b) Cementing - Surface casing

Cement service to 200 m	\$2,990
Casing wooden plug	317
Class "A" cement	340
CaCl ₂	32
Blending and delivery	264
Travel	<u>608</u>
	\$4,551

Source: Nowsco Well Services

(c) Well Screen

- Assumptions: (i) 6 lengths of 10 m long screen;
 (ii) 30 m additional for flexibility in well completion;
 (iii) 2" diameter wire wrapped stainless steel.

Well Screen	\$16,500
Delivery	<u>1,700</u>
	\$18,200

Source: Hoskin Scientific

(d) Pipe

- Assumptions: (i) 2" I.D. stainless steel flush joint liner;
 (ii) 4500 m total length.

Pipe	\$187,200
Delivery	<u>23,250</u>
	\$210,450

Source: Hoskin Scientific

(e) Development

- Assumptions: (i) Consists primarily of additional drill rig time for which 5 days is assumed and has been incorporated into the Drilling Program.

(f) Surface Casing

Assumptions: (i) 13 3/8" diameter surface casing to 200 m.

Surface Casing \$13,000

Source: Sedco Drilling

• Continuous Pressure Monitoring

Assumptions: (i) 6 completion zones;

(ii) Transducer and packer suspended on strain cable and located just above monitoring zone;

(iii) One cable reel shared for all transducers;

(iv) Data logger located at surface to record data;

(v) Electrical supply at site.

Transmitter	\$ 8,820
Transmitter cable	37,500
Packers	3,700
Packer inflation line	2,940
Strain cable	7,500
Cable reel	3,000
Data logger	20,000
Shelter (built and serviced)	<u>3,000</u>
	\$86,460

Source: SRP Control Systems, Baski Water Instruments,
In-Situ

• Initial Water Quality Sampling

(a) Analytical Costs

Assumptions: (i) Full suite of chemical analysis in all
6 wells (12 analyses);

(ii) Costs are for initial sampling only.

Indicator parameters	\$ 5,100
Priority Pollutants	12,000
isotopes (^2H , ^{13}C , ^{18}O , ^{34}S)	<u>2,400</u>
	19,500

Source: Barringer Magenta, Zenon, University of Waterloo

(b) Sampling Equipment

Assumptions: (i) 20 - 0.5 L SS sample cylinders;
(3.2 cm diameter);

(ii) Sample cylinders lowered on a wireline to which is
attached on inflation line;

(iii) Sample cylinders enclosed in SS shroud;

(iv) 2 cable reels used - one with fluid rotary.

Cable reels (2)	\$6,000
Tubing	1,700
Wireline	2,200
Shroud	1,000
Sampling cylinders (20)	8,000
Miscellaneous (i.e., regulator, gas)	<u>1,000</u>
	\$19,900

Source: Canus Plastics, R.P. Bennett,
Intera In-house records

(c) Chemist

Assumptions: (i) Involved in sampling as part of long
term monitoring plan.

Chemist	\$10,000
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In reviewing the cost summary for each of the field program alternatives outlined in Table 3.19, there are a number of factors which should be noted. In the Full Scale Testing Program, a significant portion of the total costs arises due to drill rig costs. These costs were derived based on typical drill rig costs and a drilling and testing methodology discussed with experts in the drilling industry. A full size drill rig is utilized for the entire program. The rig is costed at full rental charge through the drilling period and standby cost following drilling. However, standby costs are typically quite high and differ very little from the full rental charge. Also, given the unique nature of this program, no previous drilling projects exist for deriving cost estimates. Consultation with drilling companies has suggested that a more economical standby charge could likely be negotiated once the field program is more certain. In addition, the drilling rig costs are subject to economic climate and vary substantially on a temporal basis.

A second factor which is critical to cost is the well completion. In the full scale testing program, it is possible to reduce the completion costs by utilizing a telescoping borehole. In this way, cement and packing material quantities are reduced leading to an overall cost reduction. This option has not been evaluated.

A further factor which is significant in the well completion is the use of stainless steel well casing. Stainless steel is utilized due to its corrosion resistance and to its greater inertness. Other lower cost materials (i.e., carbon steel) could potentially be used at a sacrifice in the quality of the water quality data as well as operational problems such as scaling and precipitation/dissolution reactions.

The cost estimates prepared in this section and summarized in Table 3.19 are considered to provide realistic indication of costs which may be incurred to perform the testing and monitoring described

in earlier sections. These costs are subject to the prevailing economic climate and market fluctuations and can only be considered representative for a period of six months from the date of this report. These cost estimates should be re-evaluated and refined once the proposed field studies are better defined.

Table 3.19 presents cost estimates for a one year program but it is unlikely that the field programs would be completed in a single year. It is more likely that the programs will be carried out several fiscal years. Tables 3.20 and 3.21 present cost estimates for two and three year programs respectively with each component of the program applied to its appropriate year. The monitoring program can be effectively completed in two years and therefore a third year is not required.

It should be noted that the costs in Tables 3.19, 3.20 and 3.21 include only costs for the first pressure monitoring and groundwater sampling event. Ideally, annual or semi-annual monitoring would be completed for the duration of the project as part of the long term monitoring component.

Table 3.20 Cost Estimate for Field Program Alternatives (based on two year program)

Component	Monitoring Program (\$)		Limited Testing Program (\$)		Full Scale Testing Program (\$)	
	Year One	Year Two	Year One	Year Two	Year One	Year Two
Geologic Interpretation					486,400	
Geophysical Logging			81,400		36,200	
Hydrochemical Sampling					63,800	
Hydraulic Testing			8,500		43,700	
Long Term Monitoring	162,800	49,400	76,300	135,900		474,700
Engineering Services	14,700	4,500	15,000	12,200	56,700	42,700
TOTAL (\$)	177,500	53,900	181,200	148,100	686,800	517,400

Table 3.21 Cost Estimate for Field Program Alternatives (Based on three year program)

Component	Monitoring Program (\$)			Limited Testing Program (\$)			Full Scale Testing Program (\$)		
	Year One	Year Two	Year Three	Year One	Year Two	Year Three	Year One	Year Two	Year Three
Geologic Interpretation							486,400		
Geophysical Logging				81,400				36,200	
Hydrochemical Sampling								63,800	
Hydraulic Testing				8,500				43,700	
Long Term Monitoring	162,800	49,400			162,800	49,400		262,400	212,300
Engineering Services	14,700	4,500		8,100	14,700	4,500	43,800	36,500	19,100
TOTAL (\$)	177,500	53,900		98,000	177,500	53,900	530,200	442,600	231,400

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APPENDIX A

Tabulation of Disposal Wells within the Study Area

(Note: Some of the injection rates in Appendix A may be incorrect due to the fact that some operators consistently report the hours of disposal as 744 hours (31 day multiplied by 24 hours) regardless of actual disposal hours)

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
AMOCO B-31 LINDBERGH 7-28-55-6 W4H 00/7-28-55-6W4/0	Amoco Canada Petroleum Company Ltd.	4575	Cooking Lake	677 - 729	Potential Water Disposal - No Figures Available			
AMOCO SWD LINDBERGH 9-28-55-6 W4H 02/9-28-55-6W4/0	Amoco Canada Petroleum Company Ltd.	4227	Lloydminster	552.0 - 565.0	6856	3624 Feb 1986	90	40.26
AMOCO ET AL WDW-3 SUCDEN 13-33-62-8 W4H 00/13-33-62-8W4/0	Amoco Canada Petroleum Company Ltd.	3052A	Cummings Sand	409 - 413	Well Not On Injection			
AMOCO ET AL WDW-2 SUCDEN 2-4-63-8 W4H 00/2-4-63-8W4/0	Amoco Canada Petroleum Company Ltd.	3052	Cummings Sand	409 - 413	Potential Water Disposal - No Figures Available			
AMOCO ET AL WDW-1 SUCDEN EX 6-4-63-8 W4H AA/6-4-63-8W4/0	Amoco Canada Petroleum Company Ltd.	3052	Cummings Sand	409 - 413	15486.9	1991.0 July 1983	240	8.29
GULF COLD LAKE 1-14-65-2 W4H 00/1-14-64-2W4/0	Bow Valley Industries	4287	McMurray	517 - 562	56868.5	2193.3 Dec 1979	95	23.09
BVI LAC LA BICHE 11-19-66-3 W4H	Bow Valley Industries	4222	Grosmont	Open Hole 483.0 - 487.6	Proposed Well - Not Drilled			
BP BGUL BELLIS 12-4-60-15 W4H 02/12-4-60-15W4/0	BP Resources Canada Ltd.	2734	Camrose	661 - 671	10232.4	317.5 Jan 1986	220	1.44

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
SUPTST NUL CIGOL CRAIGEND 10-25-64-14 W4M 00/10-25-64-14W4/O	BP Exploration	3050	Grosmont A	487.9 - 491.0	22311.7	25.7 Jan 1986	705	.04
BP MARGLK WDM-1 8-7-66-5 W4M AE/8-7-66-5W4/O	BP Resources Canada Ltd.	4761	Grand Rapids	422 - 436	776805.7	14049 Sept 1984	720	19.51
BP PCI MARG LK 9-8-66-5 W4M 00/9-8-66-5W4/O	BP Resources Canada Ltd.	4761	Cambrian	1266 - 1334	Both 9-8 and 10-8 reported on 10-8			
BP PCI HANG LK 10-8-66-5 W4M 00/10-8-66-5W4/O	BP Resources Canada Ltd.	4761	Cambrian	1318 - 1334	172798.9	64125.3 June 1985	720	89.06
BP ATHORE 11-21-67-17 W4M 00/11-21-67-17W4/2	BP Resources Canada Ltd.	4127	Nisku	533.5 - 548	4087.3	412.0 Jan 1986	48	8.58
CANOXY LINDERBERG 5-18-58-4 W4M 02/5-18-58-4W4/O	Canadian Occidental Petroleum Ltd.	4522	Cooking Lake	Open Hole 604 - 614	3788.8	806.2 Dec 1985	744	1.08
WESTCOAST HANATOKAN 10-12-63-8 W4M 00/10-12-63-8W4/O	Canadian Occidental Petroleum Ltd.	4634	Cooking Lake	Open Hole 488.3 - 497.4	43304.9	357.8 Dec 1984	408	.88
CANOXY ET AL SMD WOLFLK 6-13-63-8 W4M 00/6-13-63-8W4/2	Canadian Occidental Petroleum Ltd.	4634	Cooking Lake	Open Hole 508 - 530	Well not on injection at this time			

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
CWME MURIEL LK 10-16-59-4 W4H 00/10-16-59-4W4/0	Canadian Worldwide Energy Ltd.	4201	Cummings	504 - 510	86885.7	4920.4 Jan 1984	744	6.62
SOBC BEAVER CROSSING 8-36-61-2 W4H 00.8-36-61-2W4/0	Chevron Canada Resources Ltd.	2711	Clearwater	407 - 421	225656.3	307.5 Oct 1985	21	14.64
CCL BEAVER CROSSING SWD 16-36-61-2 W4H 02/16-36-61-2W4/0	Chevron Canada Resources Ltd.	2711	Clearwater	Open Hole 414 - 442	69378.6	30.7 Sept 1985	12	2.56
CHIEFCO BLU CR CRAIGEND 3-28-64-12 W4H 00/3-28-64-12W4/0	Chieftain Development Co. Ltd.	2766	Grosmont	514.8 - 519.7	Well not on injection			
DONE ET AL LINDBERGH 100-18-55-5 W4H 00/10-18-55-4W4/0	Dome Petroleum Ltd.	3540	Rex Sand	540 - 545	403997.8	21914.8 Jan 1986	744	29.46
DONE ET AL LINDBERGH 14A-18-55-5 W4H AA/14-18-55-5W4/0	Dome Petroleum Ltd.	3540	Rex Sand	542 - 547	Well not on injection			

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
DOME ET AL LINDBERGH 3A-30-55-5 W4M 00/03-30-55-5W4/0	Dome Petroleum Ltd.	3348	Rex	548 - 554	111398.6	3695 Jan 1986	744	4.97
FINA CACHE 10-18-58-11 W4M 00/10-18-58-11W4/2	Dome Petroleum Ltd.	2418	Sparky	521.2 - 524.9	33490.2	519.1 Jan 1986	744	.69
PUBCO CRAIGEND 10-1-64-13 W4M 00/10-1-64-13W4/2	Dome Petroleum Ltd.	3310	Lower Grand Rapids	432.8 - 438.9	20224.8	1786.2 Jan 1986	657	2.72
DOME AEC 10B4 MOORE 10-5-67-4 W4M 02/10-5-67-4W4/0	Dome Petroleum Ltd.	4128	Cambrian	1303.5 - 1320.0	158664.4	17783.9 Jan 1986	744	23.9
DOME AEC 10D4 SMD HOORE 10-5-67-4 W4M 03/10-5-67-4W4/0	Dome Petroleum Ltd.	3929	McMurray	538.5 - 543.5	133632.4	1000.3 Jan 1986	336	2.98
ARDMORE THERMAL PROJECT SMD 13-20-63-13 W4M	Drummond Oil & Gas Ltd.	1945	Hannville C Sand	401.7 - 408.4	257480.2	8000.4 Nov 1985	720	11.11
ESSO 79 SMD COLDILK 7-18-64-3 W4M 00/7-18-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1248.0 - 1268.0	22514.0	22514 Sept 1985	504	44.67
ESSO 85 SMD ETHELLK 1-19-64-3 W4M 00/1-19-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	Open Hole 1245 - 1288	Potential Water Disposal - No Figures Available			
ESSO 83 SMD ETHELLK 11-22-64-3 W4M 00/11-22-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1262 - 1282	32433.4	8137.3 July 1985	559	14.56

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
ESSO 81 SWD ETHELLK 3-29-64-3 W4H 00/03-29-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1264.0 - 1284.0	Well not on injection			
ESSO 83 SWD ETHELLK 1-32-64-3 W4H 00/1-32-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1308 - 1328	430276.2	25610.0 Dec 1985	744	34.42
ESSO 83 INJ ETHELLK 8-33-64-3 W4H 00/8-33-64-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1280.6 - 1300.6	265380.8	20694 Dec 1985	744	27.81
ESSO 83 SWD ETHELLK 2-3-65-3 W4H 02/2-3-65-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1279 - 1299	478334.0	33994 Dec 1985	744	45.69
ESSO SWD LEHNG ETHELLK 3-4-65-3 W4H 00/3-4-65-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1270 - 1290	395723.1	8863 Dec 1985	744	11.91
ESSO 78 INJ ETHELLK 11-7-65-3 W4H 00/11-7-65-3W4/0	Esso Resources Canada Ltd.	4510	McMurray	518 - 530	615996.8	9611 Dec 1985	744	12.92
ESSO 79 SWD ETHELLK 12-8-65-3 W4H 00/12-8-65-3W4/0	Esso Resources Canada Ltd.	4510	Cambrian	1240 - 1260	239177.2	7884 Dec 1985	744	10.59
ESSO 78 INJ ETHELLK 4-17-65-3 W4H 00/4-17-65-3W4/0	Esso Resources Canada Ltd.	4510	McMurray	509 - 521	922932.9	8542 Dec 1985	744	11.48
HB JOHN LAKE 6-12-56-1 W4H 00/6-12-56-1W4/0	Hudson's Bay Oil & Gas Co. Ltd.	3352	Calcut Member	704 - 714	140386.9	3746 Mar 1985	600	6.24

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (± KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
HUSKY TUCKER LAKE 13A-20-64-4 WAH 00/13-20-64-4WA/0	Husky Oil Operations Ltd.	3947	McMurray	534.6 - 547.4	115977.9	8963 Jan 1986	744	12.05
KOCH SUD PT. KENT 6-19-61-4 WAH 00/6-19-61-4WA/2	Koch Exploration Ltd.	4756	Clearwater	454 - 483	No Injection figures available at this time			
MANVILLE ET AL FIGURE 2-30-64-16 WAH 00/2-30-64-16WA/0	Manville Oil & Gas Ltd.	4480	Nisku	590 - 595	Well Not On Injection			
HERLAND BRASCAN UKALTA 12-31-56-17 WAH 00/12-31-56-17WA/0	Herland Exploration Ltd.	3203	Glauconitic Sandstone	730 - 731	74902.9	907.7 Jan 1986	198	4.58
MOBIL GARTH 12-6-64-6 WAH 00/12-6-64-6WA/0	Mobil Oil Canada Ltd.	4755	Cambrian	1349 - 1364	10504.5	4753.8 Jan 1986	744	6.39
MOBIL GARTH 6-11-64-6 WAH 00/6-11-64-6WA/0	Mobil Oil Canada Ltd.	3779	Clearwater	439 - 447	101763.4	5586.1 Nov 1985	480	11.64
MURPHY BOCO P1-3 LIND EX 5-13-58-5 WAH 00/5-13-58-5WA/0	Murphy Oil Company Ltd.	2220	Lower Grand Rapids	509.3 - 511.8	292149.4	8421.4 Feb 1985	672	12.53
MURPHY SUD FWD 2 LIND 5-13-58-5 WAH 02/5-13-58-5WA/0	Murphy Oil Company Ltd.	4312	Cooking Lake	Open Hole 578 - 615	91531.8	6427 Jan 1986	744	8.64
BOCO ET AL LINDBERGH 4-14-58-5 WAH 00/4-14-58-5WA/0	Murphy Oil Company Ltd.	2075	Grand Rapids	511.1 - 514.5	11129.5	155 Nov 1980	720	.22

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (m KE)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
NOVALTA UNIT SWD CHARRON 11-3-69-16 W4H 0/1-3-69-16W4/2	Novalta Resources Ltd.	2482	Grosmont	489.2 - 491.6	22845	8.5 Dec 1985	744	.01
NOVALTA SWD CASLAN 11-8-65-17 W4H 00/11-8-65-17W4/0	Novalta Resources Ltd.	4497	Grosmont	Open Hole 640 - 675.3	Potential Water Disposal - No Figures Available			
PCP LINDBERGH 10-9-55-6 W4H 00/10-9-55-6W4/2	PanCanadian Petroleum Ltd.	4753	Lloydminster	553 - 568	25494.1	1681.8 Dec 1985	63	26.69
PCP LINDBERGH 6-3-56-6 W4H 02/6-3-56-6W4/0	PanCanadian Petroleum Ltd.	4753	Lloydminster	555 - 575	746.7	746.7 Jan 1986	368	2.03
PROVIDENT HANNORE 6-1-61-17 W4H 00/6-1-61-17W4/0	Sceptre Resources Ltd.	2452	Glauconitic Sandstone	644 - 649	61260.5	776.3 Jan 1986	70	11.09
SULPETRO LINDBERGH 13-36-54-6 W4H 00/13-36-54-5W4/2	Sulpetro Limited	3398	Cooking Lake	Open Hole 635 - 655	9086.5	74 Jan 1986	3	24.67
SUNCOR WECO FT KENT 2-28-61-4 W4H 02/2-28-61-4W4/0	Suncor Inc.	3618	Cummings	412 - 457	694426	18341 Jan 1986	684	26.81
SUNCOR CWNE FT KENT 5A-28-61-4 W4H A2/5-28-61-4W4/0	Suncor Inc.	3618	Cummings	499.6 - 502.6	253.9	253.9 Sept 1976	720	.35
SUNCOR CWNE FT KENT 5A-28-61-4 W4H A2/5-28-61-4W4/2	Suncor Inc.	3618	Clearwater	443.8 - 452.3	1617720.1	19428 Jan 1986	684	28.4

WELL NAME WELL LOCATION WELL UNIQUE ID	COMPANY NAME	APPROVAL NUMBER	DISPOSAL FORMATION	PERFORATED INTERVAL TOP AND BASE (= KB)	CUM. VOLUME INJECTED (m ³)	LAST MONTH VOLUME INJECTED (m ³)	HOURS OF INJECTION	AVERAGE RATE m ³ /HR
SUNCOR CWME FT KENT 5A-28-61-4 WAH 03/5-28-61-4 WAH/0	Suncor Inc.	3618	Clearwater	412 - 458	173183.5	575 Dec 1980	9	63.89
ELK POINT HD. 7 7-25-56-5 WAH 00/7-25-56-5 WAH/0	The Canadian Salt Co. Ltd.	4088	Lindbergh Sparky	415.7 - 416.9	11231.4	27.5 Oct 1984	2	13.75
SIAL ATHORE 11-23-67-18 WAH 00/11-23-67-18 WAH/2	Thompson-Jensen Petroleum Ltd.	3042	Nisku	542.5 - 545.6	42671.9	1315.3 Jan 1986	744	1.77
GEORG ET AL HTLO 6-3-67-14 WAH 00/6-3-67-14 WAH/0	Ultramar Oil & Gas of Canada Ltd.	3294	Grosmont	521 - 522 (Open hole)	9618.2	59.6 Jan 1986	713	.08
IMPERIAL WILLINGDON NO. 1 14-14-55-15 WAH 00/14-14-55-15 WAH/0	Westmain Resources Ltd.	3227	Willingdon D-3B	656.7 - 659.1	63110.7	3443.1 Jan 1986	744	4.63
WESTMIN LINDBERGH 11-1-55-5 WAH 00/11-1-55-5 WAH/2	Westmain Resources Ltd.	3617	Lloydminster Sand	516.5 - 529	76906.3	1854 Jan 1986	480	3.86
BRASCAN LINDBERGH 6-27-55-5 WAH 00/6-27-55-5 WAH/2	Westmain Resources Ltd.	3976	Lloydminster Sand	532 - 536	62853.8	1253 Jan 1986	432	2.90
WESTMIN LINDBERGH 3-13-55-6 WAH 00/3-13-55-6 WAH/0	Westmain Resources Ltd.	4500	Cooking Lake	Open Hole 665 - 708	47968	2615 Jan 1986	600	4.36
MINERALS HARRY 7-22-55-14 WAH 00/7-22-55-14 WAH/2	Westmain Resources Ltd.	3691	Nisku	652.3 - 648.6	350947.6	5382.7 Jan 1986	720	7.48

APPENDIX B

Hydrostratigraphic Unit Evaluation

- Rankings

Mannville Group

A. Geologic Information

A1. Frequency of Structural Discontinuities

No frequently occurring structural features were reported in references reviewed on the Mannville Group. The entire formation was ranked as having a low frequency of structural discontinuities.

A2. Proximity to Major Structural Influences on Groundwater Flow

The collapse zone overlying the edge of the Prairie Formation is considered as a major structural influence. It should be noted that the limits of this collapse zone have not been identified in previous studies. For this study, the limits used were the area overlying the subcrop of the Prairie Formation (Figure 2.9). This is likely a reasonably good estimate of the extent of the collapse feature but possibly underestimates the eastern limit where the Prairie has completely dissolved.

The edge of the Clearwater Formation was also considered as a major structural feature. This formation is less than 10 m thick yet is reported to act as an aquitard isolating flow between the Upper and Lower Mannville Group. In the area where the Clearwater is absent, the Upper and Lower Mannville are hydraulically connected. It should be noted that the edge of the Clearwater is not documented in Saskatchewan. The net result of not knowing where the Clearwater is absent in this province is to favour this portion of the study area over the area where no Clearwater is present.

B. Hydrogeologic Information

B1. Proximity to Groundwater Discharge Zone(s)

The possibility of groundwater discharge from the Upper Mannville Group to buried valley aquifers was identified by both Meneley (1983a) and ARC (1985i). Although this has not been studied in any detail and has not been confirmed through field studies, it is presumed that groundwater discharge does occur to the major buried valleys in the study area. This assumption falls in line with that of the Mannville Group being located in the intermediate groundwater flow system. The location of buried valleys, primarily that of the Empress Group, were obtained from a number of sources (Gold et al., 1983; Yoon and Pluym, 1974; Whitaker and Christiansen, 1972; Whitaker and Pearson, 1972; ARC, 1985g; Meneley, 1983a; Carlson, 1972; Carlson and Currie, 1975) with the approximate alignments shown on Figure 2.10. The location of these valleys varies in different reports and the alignments shown are a composite of the available information. Also, the valleys were not mapped over the entire study area such that some of the valleys shown are discontinuous.

B2. Formation Transmissivity

A transmissivity of somewhat greater than $10^{-4} \text{ m}^2/\text{s}$ was calculated and exists throughout the entire study area. This was based on a permeability of 10^{-13} m^2 (Tables 2.1 and 2.4) which is the equivalent of a hydraulic conductivity of 10^{-6} m/s using fresh water as the fluid. The formation thickness was obtained from ARC (1985g) and McCrossan and Glaister (1964).

B3. Formation Permeability

The range of permeabilities reported for the Mannville Group is 10^{-14} to 10^{-12} m^2 . A formation permeability of 10^{-9} cm^2 was used in the constraint mapping.

B4. Matrix Porosity

A matrix porosity of 33% was used (see Tables 2.1 and 2.4).

B5. Injection Zone Continuity/Area Extent

The Mannville Group is relatively continuous throughout the study area (ARC, 1985g; McCrossan and Glaister, 1964).

B6. Containment Capabilities/Integrity of Confining Units

The formation which is most important in confining formation fluids within the Mannville is the overlying Colorado Group with the exception of perhaps the Viking Sandstone. The Colorado Group is intact throughout the study area. However, ARC (1985g) reports that some evidence of collapse features in the Prairie Formation is evident throughout the Cretaceous. As a consequence, the integrity of the Colorado Group is suspect in the vicinity of the Prairie Formation subcrop.

The Clearwater Formation also affects the containment of the Mannville although likely to a much lesser extent than the Colorado Group. Thus, the containment of the Mannville Group is considered to be somewhat reduced where the Clearwater is absent.

B7. Primary Groundwater Flow System

The Mannville Group is considered to be situated within the intermediate groundwater flow system at all locations based on the findings of ARC (1985i) and Meneley (1983a).

B8. Breach Potential due to Abandoned or Active Oil and Gas Wells

A high potential for breach of the injection formation is considered to exist in the areas where oil and gas reserves are known to be present within the Lower Cretaceous (Figure 3.1). This information was obtained from ARC (1985a) and was only available for the Alberta portion of the study area. As a result, a bias exists towards selection of the Saskatchewan portion of the Mannville Group.

B9. Potential for Hydraulic Communication with Potable Water Supplies

The potential for hydraulic communication and subsequent contamination of potable groundwater supplies due to discharge from the Mannville Group was considered high at all locations due to the potential connection to buried valley aquifers (see Section 2.2.1.7).

B10. Injection Formation Depth Below Surface

The Mannville Group is the shallowest candidate injection horizon and is ranked accordingly.

C. Resource Information:

C1. Future Resource Potential of Formation

The future resource potential of the Mannville Group is ranked as high where hydrocarbons are known to exist and intermediate where they do not according to information presented in ARC (1985a) and shown in Figure 3.1.

C2. Potential Interference with Existing Resource
Extraction Sectors

The potential interference of waste injection operations with resource extraction was considered high where hydrocarbon resources are known to exist and intermediate elsewhere (Figure 3.1).

Cooking Lake - Beaverhill Lake - Watt Mountain Group Aquifer
(CBWA)

A. Geologic Information:

A1. Frequency of Structural Discontinuities

No frequent structural discontinuities are reported for the CBWA.

A2. Proximity to Major Structural Influences on Groundwater Flow

The area of collapse features in the vicinity of the solution edge of the Prairie Formation is considered as a structural feature affecting groundwater flow. The bounds of the collapse zone were assumed to correspond to the subcrop of the Prairie Formation as discussed for the Mannville Group (Section 3.1.1) and shown in Figure 2.8.

B. Hydrogeologic Information:

B1. Proximity to Groundwater Discharge Zone(s)

The zone of groundwater discharge for the CBWA is considered to be the area where it subcrops. That is, the area east of the pinch out of the overlying Ireton Shale (Figures 2.4 and 2.8). The edge of the CBWA lies to the east and north of the study area.

B2. Formation Transmissivity

The formation transmissivity was calculated based on a formation permeability of 10^{-13} m² (see Table 2.2) and a formation thickness derived from ARC (1985g) and McCrossan and Glaister

(1964). The transmissivity was calculated as between 10^{-4} and 10^{-2} m^2/s throughout most of Alberta and southeast Saskatchewan. In the remainder of Saskatchewan, the transmissivity was less than 10^{-4} m^2/s . It should be noted that the location of the isopach corresponding to a transmissivity of 10^{-4} m^2/s is somewhat uncertain in Saskatchewan.

B3. Formation Permeability

The reported values for permeability ranged from 10^{-16} to 10^{-12} m^2 (see Table 2.2). A value of 10^{-13} m^2 was used in the constraint mapping.

B4. Matrix Porosity

A matrix porosity of 13% was used in the constraint mapping (see Table 2.2).

B5. Injection Zone Continuity/Areal Extent

The injection zone is considered to have limited continuity in the subcrop zone and to be continuous where it is fully intact west of the edge of the overlying Ireton Shale (Figures 2.4 and 2.8).

B6. Containment Capabilities/Integrity of Confining Units

The containment capabilities of the Ireton Shale are considered to be high where the shale is present at its full formation thickness in the extreme southwest part of the study area (Figures 2.4 and 2.8). The confining unit has limited continuity where the Ireton subcrops and where it thins beneath the Grosmont. The containment capabilities were ranked low where the Ireton is absent and where the collapse zones exist overlying the solution edge of the Prairie Formation.

B7. Primary Groundwater Flow System

The CBWA is considered to exist within the deep regional groundwater flow system where the Ireton is present and within the intermediate flow system elsewhere where it is connected to the Mannville Group (ARC, 1985i).

B8. Breach Potential due to Abandoned or Active Oil and Gas Wells

This breach potential is considered intermediate where the CBWA subcrops below known oil and gas reserves as shown in Figure 3.1 (from ARC, 1985a) and low elsewhere.

B9. Potential for Hydraulic Communication with Potable Water Supplies

The potential for hydraulic communication with potable water supplies is ranked as low where the Ireton Formation is present and intermediate where it is not.

B10. Injection Formation Depth Below Surface

The CBWA is the second most deep candidate injection formation and is ranked accordingly.

C. Resource Information:

C1. Future Resource Potential

No resources are known to exist with the CBWA.

C2. Potential Interference with Existing Resource Extraction Sectors

No resource extraction operations currently exist within or below the CBWA.

Cambrian/Granite Wash

A. Geologic Information:

A1. Frequency of Structural Discontinuities

In reviewing the available information (Meneley 1983a; Pugh, 1971) on the Cambrian/Granite Wash, no frequent structural discontinuities were reported.

A2. Proximity to Major Structural Influences on Groundwater Flow

The edge of the Cambrian/Granite Wash in the northern portion of the study area (Figure 2.7) is a major influencing factor on groundwater flow. Portions of the formation near the formation edge are not favoured for waste fluid injection.

The area in the vicinity of the solution edge of the Prairie Formation is also considered as a major structural influence on groundwater flow (Figure 2.7).

B1. Proximity to Groundwater Discharge Zone

The edge of the Cambrian/Granite Wash and the area where the Prairie Formation is absent (except where the Meadow Lake Escarpment is absent) are considered as groundwater discharge zones for this formation (Figures 2.4 and 2.7).

B2. Formation Transmissivity

A permeability of 10^{-12} m² was selected in calculating the formation transmissivity (see Tables 2.3 and 2.6). The transmissivity exceeds 10^{-4} m²/s in all locations where the

formation thickness exceeds 10 m. The 10 m isopach was interpolated from the 100 and zero isopach contours presented in Meneley (1983a) and was found to lie within approximately 5 km of the edge of the formation.

B3. Formation Permeability

A permeability of 10^{-12} m² (see Tables 2.3 and 2.6), which is equivalent to a hydraulic conductivity of 10^{-5} m/s (using dilute water as the interstitial fluid), was used in the constraint mapping.

B4. Matrix Porosity

A matrix porosity of 20% was used in constraint mapping (see Tables 2.3 and 2.6).

B5. Injection Zone Continuity/Areal Extent

The exact location of discontinuous zones within the Cambrian/Granite Wash are unknown although they are reported to exist to the north of Cold Lake (Meneley, 1983a). The 10 m isopach was arbitrarily selected as the boundary of the discontinuous zone. This formation was considered to be continuous to the south-southeast of the Meadow Lake Escarpment and of limited continuity elsewhere (Figure 2.7).

B6. Containment Capabilities/Integrity of Confining Units

The formation confining groundwater flow to the Prairie Formation. The containment capabilities of the Prairie Formation are considered as high where it is fully intact, intermediate where it subcrops and low where it is absent as shown on Figure 2.7.

B7. Primary Groundwater Flow System

The Cambrian/Granite Wash Formation is considered to lie within the deep groundwater flow system where the Prairie Formation is present. Where the Prairie Formation is absent, the Cambrian/Granite Wash reportedly coalesces with the CBWA and the Mannville Group and is considered to exist within the intermediate flow system.

B8. Breach Potential due to Abandoned or Active Oil and Gas Wells

The breach potential is considered as low for the entire Cambrian/Granite Wash.

B9. Potential for Hydraulic Communication with Potable Water Supplies

This potential is ranked as low where the Cambrian/Granite Wash Formation is confined by the Prairie Formation and intermediate elsewhere.

B10. Injection Formation Depth Below Surface

The Cambrian/Granite Wash is the deepest candidate injection formation.

C. Resource Information:

C1. Future Resource Potential of Formation

No resource potential is known to exist within the Cambrian/Granite Wash.

C2. Potential Interference with Existing Resource Extraction Sectors

No resource extraction operations exist with the Cambrian/Granite Wash.

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue
55	16 w3	5	10	5	5	3	5	10	1	3	10	10	10	5	5	87
	17	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	18	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	19	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	20	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	21	5	10	1	5	3	5	10	1	3	10	10	10	5	5	83
	22	5	5	1	5	3	5	10	1	3	10	10	10	5	5	78
	23	5	1	1	5	3	5	10	1	5	10	20	10	5	5	86
	24	5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
	25	5	5	1	5	3	5	5	5	5	10	20	10	5	5	89
	26	5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
	27	5	10	3	5	3	5	5	5	5	10	20	10	5	5	96
	1 w4	5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
	2	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	3	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	4	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	5	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	6	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	7	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	8	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	9	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	10	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	11	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	12	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	13	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	14	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	15	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	16	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	17	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
56	16 w3	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	17	5	10	3	5	3	5	10	1	3	10	10	10	5	5	85
	18	5	10	1	5	3	5	10	1	3	10	10	10	5	5	83
	19	5	10	1	5	3	5	10	1	3	10	10	10	5	5	83
	20	5	10	1	5	3	5	10	1	3	10	10	10	5	5	83
	21	5	10	1	5	3	5	10	1	3	10	10	10	5	5	78
	22	5	5	1	5	3	5	5	1	3	10	10	10	5	5	73

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
23		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
24		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
25		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
26		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
27		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
1 W4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
2		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16 W3		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
17		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
18		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
19		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
20		5	10	1	5	3	5	5	1	3	10	10	10	5	5	83
21		5	10	1	5	3	5	5	1	3	10	10	10	5	5	83
22		5	5	1	5	3	5	5	1	3	10	10	10	5	5	78
23		5	5	1	5	3	5	5	1	3	10	10	10	5	5	78
24		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
25		5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
26		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
27		5	10	3	5	3	5	5	5	5	10	20	10	5	5	96
1 W4		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
2		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sua	
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
16 w3		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
17		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
18		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
19		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
20		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
21		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
22		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78	
23		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73	
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73	
25		5	1	1	5	3	5	5	5	5	10	20	10	5	5	85	
26		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91	
27		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91	
1 w4		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98	
2		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103	

Table 8-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16 w3		5	10	1	5	3	5	5	1	3	10	10	10	5	5	103
17		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
18		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
19		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
20		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
21		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
22		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
23		5	5	1	5	3	5	5	1	3	10	10	10	5	5	78
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
25		5	1	1	5	3	5	5	1	3	10	10	10	5	5	73
26		5	5	3	5	3	5	5	5	5	10	10	10	5	5	69
27		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
1 w4		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
2		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue
60	17	5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
	16 W3	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	17	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	18	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	19	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	20	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	21	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	22	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	23	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	24	5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
	25	5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
	26	5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
	27	5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
	1 W4	5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
	2	5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
	3	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	4	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	5	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	6	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	7	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	8	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	9	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	10	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	11	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	12	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	13	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
	14	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103
15	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103	
16	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103	
17	5	10	5	5	3	5	5	5	10	5	10	20	10	5	103	
61	16 W3	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	17	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	18	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	19	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	20	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	21	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	22	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	23	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	24	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
	25	5	10	1	5	3	5	5	1	3	10	10	10	5	5	78

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
22		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
23		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
25		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
26		5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
27		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
1	4	5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
2		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
62	16	3	10	1	5	3	5	5	1	3	10	10	10	5	5	78
17		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
18		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
19		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
20		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
21		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
22		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
23		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
25		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
26		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
27		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
1	4	5	5	3	5	3	5	5	5	5	10	20	10	5	5	91

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue
2		5	10	5	5	3	5	5	5	5	10	20	10	5	5	98
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16 w3		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
17		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
18		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
19		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
20		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
21		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
22		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
23		5	10	1	5	3	5	5	1	3	10	10	10	5	5	78
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
25		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
26		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
27		5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
1 w4		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
2		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sua
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16 w3		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
17		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
18		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
19		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
20		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
21		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
22		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
23		5	10	1	5	3	5	5	1	3	10	10	10	5	5	73
24		5	5	1	5	3	5	5	1	3	10	10	10	5	5	78
25		5	5	1	5	3	5	5	1	3	10	10	10	5	5	73
26		5	1	1	5	3	5	5	1	3	10	10	10	5	5	73
27		5	1	1	5	3	5	5	5	5	10	20	10	5	5	69
1 w4		5	5	3	5	3	5	5	5	5	10	20	10	5	5	85
2		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
3		5	10	5	5	3	5	5	10	5	10	20	10	5	5	91
4		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
5		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
6		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking														Sum
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	
21		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22		5	1	1	5	3	5	1	1	3	10	10	10	5	5	65
23		5	1	1	5	3	5	1	1	3	10	10	10	5	5	65
24		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
25		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
26		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
27		5	1	1	5	3	5	5	1	3	10	10	10	5	5	69
1	4	5	1	1	5	3	5	5	5	5	10	20	10	5	5	85
2		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
3		5	5	3	5	3	5	5	5	5	10	20	10	5	5	91
4		5	5	3	5	3	5	5	10	5	10	20	10	5	5	96
5		5	5	3	5	3	5	5	10	5	10	20	10	5	5	96
6		5	5	3	5	3	5	5	10	5	10	20	10	5	5	96
7		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
8		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
9		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
10		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
11		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
12		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
13		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
14		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
15		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
17		5	10	5	5	3	5	5	10	5	10	20	10	5	5	103
16	3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
17		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
18		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
24		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
25		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
27		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table B-1. Hydrostratigraphic Unit Evaluation - Cambrian Granite Wash Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue	
68	1 W4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	2	5	1	1	1	3	5	1	5	5	10	20	10	5	5	77	
	3	5	1	1	1	3	5	5	5	5	10	20	10	5	5	77	
	4	5	1	1	1	3	5	5	10	5	10	20	10	5	5	86	
	5	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	6	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	7	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	8	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	9	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	10	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	11	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	12	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	13	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	14	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	15	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	16	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	17	5	5	3	5	3	5	5	10	5	10	20	10	5	5	96	
	16 W3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
	17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	23	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
27	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
1 W4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
6	5	1	1	1	1	3	5	1	10	5	10	20	10	5	5	82	
7	5	1	5	3	5	3	5	1	10	5	10	20	10	5	5	86	

Table B-1. Hydrostratigraphic Unit Evaluation - Caebrian Granite Wash Ranking

[illegible]

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														Sum	
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2		
55	16 w3	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	22	5	5	1	5	3	1	5	1	3	10	10	5	5	5	65	
	23	5	1	1	5	3	1	5	1	3	10	10	5	5	5	64	
	24	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	25	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	26	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	27	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	1 w4	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	2	5	5	1	5	3	1	5	1	3	10	10	5	5	5	60	
	3	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
	4	5	10	3	5	3	1	10	1	3	10	10	5	5	5	69	
	5	5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
	6	5	10	5	5	3	1	10	5	5	10	20	5	5	5	92	
	7	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	8	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	9	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	10	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	11	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	12	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	13	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	14	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	15	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
	16	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
	17	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
56	16 w3	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
	22	5	5	1	5	3	1	5	1	3	10	10	5	5	5	69	
		5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
		5	5	1	5	3	1	5	1	3	10	10	5	5	5		
		5	5	1	5	3	1	5	1	3	10	10	5	5	5		

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sua	
57	23	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
	24	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	25	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	26	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	27	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
	1 #4	5	10	1	5	3	1	5	1	3	10	5	5	5	3	62	
	2	5	10	1	5	3	1	5	1	3	10	5	5	5	3	62	
	3	5	5	1	5	3	1	5	1	3	10	5	5	5	3	57	
	4	5	10	3	5	3	1	10	5	5	5	10	20	5	5	92	
	5	5	10	3	5	3	1	10	5	5	5	10	20	5	5	92	
	6	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	7	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	8	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	9	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	10	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	11	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	12	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	13	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	14	5	10	5	5	3	1	10	5	5	5	10	20	5	5	94	
	15	5	10	5	5	3	1	10	5	5	5	10	20	5	5	99	
	16	5	10	5	5	3	1	10	5	5	5	10	20	5	5	99	
	17	5	10	5	5	3	1	10	5	5	5	10	20	5	5	99	
	16 #3	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	65
	17	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	65
	18	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	65
	19	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	65
	20	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	65
21	5	10	1	1	1	3	1	5	1	3	10	10	5	5	5	69	
22	5	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
23	5	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
24	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
25	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
26	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
27	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
1 #4	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
2	5	1	1	1	5	3	1	5	1	3	10	10	5	5	5	53	

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area			Ranking															
Township	Range	Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum	
3			5	5	1	5	3	1	5	1	3	5	10	5	5	3	57	
4			5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
5			5	10	1	5	3	1	10	5	5	10	20	5	5	5	90	
6			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
7			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
8			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
9			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
10			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
11			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
12			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
13			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
14			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
15			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
16			5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
17			5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
16 #3			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
17			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
18			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
19			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
20			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
21			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
22			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
23			5	10	1	5	3	1	5	1	3	10	10	5	5	5	69	
24			5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
25			5	5	1	5	3	1	5	1	3	10	10	5	5	5	64	
26			5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
27			5	1	1	5	3	1	5	1	3	10	10	5	5	5	60	
1 #4			5	1	1	5	3	1	5	1	3	5	10	5	5	3	53	
2			5	1	1	5	3	1	5	1	3	5	10	5	5	3	53	
3			5	5	1	5	3	1	5	1	3	5	10	5	5	3	57	
4			5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
5			5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
6			5	10	1	5	3	1	10	5	5	10	20	5	5	5	67	
7			5	10	1	5	3	1	10	5	5	10	20	5	5	5	90	
8			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
9			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Matt Mountain Group Aquifer Ranking

Township	Area Range Meridian	Ranking														Sum
		A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	
10		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
11		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
12		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
16		5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
17		5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
16 #3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
17		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
18		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
19		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
20		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
21		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
23		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
24		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
25		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
26		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
27		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
1 #4		5	1	1	5	3	1	5	1	3	10	10	5	5	5	53
2		5	1	1	5	3	1	5	1	3	10	10	5	5	5	53
3		5	5	1	5	3	1	5	1	3	10	10	5	5	5	57
4		5	10	1	5	3	1	5	1	3	10	10	5	5	5	62
5		5	10	1	5	3	1	5	1	3	10	10	5	5	5	62
6		5	10	1	5	3	1	5	5	3	10	10	5	5	5	66
7		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
8		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
9		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
10		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
11		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
12		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
16		5	10	5	5	3	1	10	10	5	10	20	5	5	5	99

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sub
60	17	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
	16 w3	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	22	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	23	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	24	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64
	25	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
	26	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
	27	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
	1 w4	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
	2	5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
	3	5	5	1	5	3	1	5	1	3	10	10	5	5	5	60
	4	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64
	5	5	5	1	5	3	1	5	1	3	10	10	5	5	5	64
	6	5	10	1	5	3	1	5	1	3	10	10	5	5	5	67
	7	5	10	1	5	3	1	5	1	3	10	10	5	5	5	67
	8	5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
	9	5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
	10	5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
	11	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
	12	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
	13	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
	14	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15	5	10	5	5	3	1	10	10	5	10	20	5	5	5	94	
16	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
17	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99	
61	16 w3	5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Wat' Mountain Group Aquifer Ranking

Area		Ranking															
Township	Range	Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
22			5	10	1	1	3	1	5	1	3	10	10	3	5	5	65
23			5	10	1	1	3	1	5	1	3	10	10	3	5	5	65
24			5	5	1	1	3	1	5	1	3	10	10	3	5	5	60
25			5	5	1	1	3	1	5	1	3	10	10	3	5	5	60
26			5	1	1	1	3	1	5	1	3	10	10	3	5	5	56
27			5	1	1	1	3	1	5	1	3	10	10	3	5	5	56
1	4		5	1	1	5	3	1	5	1	3	5	10	3	5	3	53
2			5	1	1	5	3	1	5	1	3	5	10	3	5	3	53
3			5	5	1	5	3	1	5	1	3	5	10	3	5	3	57
4			5	5	1	5	3	1	5	1	3	5	10	3	5	3	57
5			5	10	1	5	3	1	5	1	3	5	10	3	5	3	62
6			5	10	1	5	3	1	5	1	3	5	10	3	5	3	62
7			5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
8			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
9			5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
10			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
11			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
12			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15			5	10	5	5	3	1	10	10	5	10	20	5	5	5	99
16			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
17			5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16	3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
17			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
18			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
19			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
20			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
21			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
22			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
23			5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
24			5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
25			5	5	1	5	3	1	5	1	3	10	10	5	5	5	64
26			5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
27			5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
1	4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue
2		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
3		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
4		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
5		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
6		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
8		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
9		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
10		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
11		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
12		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
17		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16 #3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
17		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
18		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
19		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
20		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
21		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
23		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
24		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
25		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
26		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
27		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
1 #4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
2		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
3		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
4		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
5		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
6		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
8		5	10	1	5	3	1	5	1	3	5	10	5	5	3	90

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Township	Area	Ranking														Sum
		A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	
9		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
10		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
11		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
12		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
17		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16 w3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
17		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
18		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
19		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
20		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
21		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
23		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
24		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
25		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
26		5	1	1	1	3	1	5	1	3	10	10	5	5	5	56
27		5	1	1	5	3	1	5	1	3	10	10	5	5	5	60
1 w4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
2		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
3		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
4		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
5		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
6		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
8		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
9		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
10		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
11		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
12		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
65	16	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
	17	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
	16 W3	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	21	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	22	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	23	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	24	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	25	5	5	1	1	3	1	5	1	3	10	10	5	5	5	65
	26	5	1	1	1	3	1	5	1	3	10	10	5	5	5	60
	27	5	1	1	1	3	1	5	1	3	10	10	5	5	5	56
	1 W4	5	1	1	1	3	1	5	1	3	5	10	5	5	5	56
	2	5	1	1	1	5	3	1	5	1	3	5	10	5	5	49
	3	5	1	1	1	5	3	1	5	1	3	5	10	5	5	53
	4	5	5	1	5	3	1	5	1	3	5	10	5	5	5	53
	5	5	5	1	5	3	1	5	1	3	5	10	5	5	5	57
	6	5	10	1	5	3	1	5	1	3	5	10	5	5	5	57
	7	5	10	1	5	3	1	5	1	3	5	10	5	5	5	62
	8	5	10	1	5	3	1	5	1	3	5	10	5	5	5	62
	9	5	10	1	5	3	1	5	1	3	5	10	5	5	5	62
	10	5	10	1	5	3	1	5	1	3	5	10	5	5	5	62
	11	5	10	1	5	3	1	5	1	3	5	10	5	5	5	90
	12	5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
	13	5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
14	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
15	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
16	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
17	5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
66	16 W3	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	17	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	18	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	19	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
	20	5	10	1	1	3	1	5	1	3	10	10	5	5	5	65

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
21		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
23		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
24		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
25		5	5	1	1	3	1	5	1	3	10	10	5	3	5	60
26		5	5	1	1	3	1	5	1	3	10	10	5	3	5	60
27		5	1	1	1	3	1	5	1	3	10	10	5	3	5	60
1	W4	5	1	1	5	3	1	5	1	3	5	10	5	3	3	56
2		5	1	1	5	3	1	5	1	3	5	10	5	3	3	53
3		5	1	1	5	3	1	5	1	3	5	10	5	3	3	53
4		5	1	1	5	3	1	5	1	3	5	10	5	3	3	53
5		5	5	1	5	3	1	5	1	3	5	10	5	3	3	53
6		5	10	1	5	3	1	5	1	3	5	10	5	3	3	57
7		5	10	1	5	3	1	5	1	3	5	10	5	3	3	62
8		5	10	1	5	3	1	5	1	3	5	10	5	3	3	62
9		5	10	1	5	3	1	5	1	3	5	10	5	3	3	62
10		5	10	1	5	3	1	5	1	3	5	10	5	3	3	62
11		5	10	1	5	3	1	5	1	3	10	10	5	3	5	69
12		5	10	3	5	3	1	10	5	5	10	20	5	3	5	90
13		5	10	5	5	3	1	10	5	5	10	20	5	3	5	92
14		5	10	5	5	3	1	10	5	5	10	20	5	3	5	94
15		5	10	5	5	3	1	10	5	5	10	20	5	3	5	94
16		5	10	5	5	3	1	10	5	5	10	20	5	3	5	94
17		5	10	1	5	3	1	10	5	5	10	20	5	3	5	90
67	W3	5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
17		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
18		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
19		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
20		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
21		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
23		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
24		5	10	1	1	3	1	5	1	3	10	10	5	3	5	65
25		5	5	1	1	3	1	5	1	3	10	10	5	3	5	60
26		5	5	1	1	3	1	5	1	3	10	10	5	3	5	60
27		5	1	1	1	3	1	5	1	3	10	10	5	3	5	56

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Matt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
1 W4		5	1	1	1	3	1	5	1	3	10	10	5	5	5	56
2		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49
3		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
5		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
6		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
8		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
9		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62
10		5	10	1	5	3	1	5	1	3	10	10	5	5	5	69
11		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90
12		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
17		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16 W3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
17		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
18		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
19		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
20		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
21		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
22		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
23		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
24		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
25		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65
26		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60
27		5	1	1	1	3	1	5	1	3	10	10	5	5	5	56
1 W4		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49
2		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49
3		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53
5		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
6		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum	
8		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
9		5	10	1	5	3	1	5	1	5	5	20	5	5	3	74	
10		5	10	1	5	3	1	5	1	5	10	20	5	5	5	81	
11		5	10	1	5	3	1	10	5	5	10	20	5	5	5	90	
12		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
16		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
17		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
16 n3		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
17		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
18		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
19		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
20		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
21		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
22		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
23		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
24		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
25		5	10	1	1	3	1	5	1	3	10	10	5	5	5	65	
26		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60	
27		5	5	1	1	3	1	5	1	3	10	10	5	5	5	60	
1 n4		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49	
2		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49	
3		5	1	1	1	3	1	5	1	3	5	10	5	5	3	49	
4		5	1	1	5	3	1	5	1	3	5	10	5	5	3	53	
5		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57	
6		5	5	1	5	3	1	5	1	3	5	10	5	5	3	57	
7		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
8		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
9		5	10	1	5	3	1	5	1	3	5	10	5	5	3	62	
10		5	10	1	5	3	1	5	1	3	10	20	5	5	5	85	
11		5	10	3	5	3	1	5	1	3	10	20	5	5	5	87	
12		5	10	3	5	3	1	10	5	5	10	20	5	5	5	92	
13		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	
14		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94	

Table B-2. Hydrostratigraphic Unit Evaluation - Cooking Lake-Beaverhill Lake-Watt Mountain Group Aquifer Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
15		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
16		5	10	5	5	3	1	10	5	5	10	20	5	5	5	94
17		5	10	5	5	3	10	10	5	5	1	1	5	1	1	67

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue
23		5	5	1	5	3	10	10	10	3	10	1	1	5	5	74
24		5	1	1	5	3	10	10	10	3	10	1	1	5	5	70
25		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
26		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
27		5	1	5	5	3	10	10	5	3	10	1	1	5	5	69
1 W4		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
3		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
4		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
5		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
6		5	1	1	5	3	10	10	5	3	5	1	1	3	3	56
7		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
8		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
9		5	1	5	5	3	10	10	5	3	5	1	1	3	3	60
10		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72
11		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72
12		5	5	1	5	3	10	10	10	3	10	1	1	5	5	74
13		5	5	3	5	3	10	10	10	3	10	1	1	5	5	74
14		5	5	1	5	3	10	10	10	3	10	1	1	5	5	74
15		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
16		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
17		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16 W3		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
18		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
19		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
20		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76
23		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76
24		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72
25		5	1	1	5	3	10	10	5	3	10	1	1	5	5	65
26		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
27		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
1 W4		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sub
3		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
4		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
5		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
6		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
7		5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
8		5	1	3	5	3	10	10	10	3	5	1	1	3	3	63
9		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
10		5	5	3	5	3	10	10	10	3	5	1	1	3	3	67
11		5	5	1	5	3	10	10	10	3	5	1	1	3	3	65
12		5	5	1	5	3	10	10	10	3	5	1	1	3	3	65
13		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
14		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
15		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
17		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16 W3		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
18		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
19		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
20		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76
24		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76
25		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
26		5	1	1	5	3	10	10	5	3	10	1	1	5	5	65
27		5	1	1	5	3	10	10	5	3	10	1	1	5	5	65
1 W4		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
2		5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
3		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
4		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
5		5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
6		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
7		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
8		5	5	3	5	3	10	10	10	3	5	1	1	3	3	67
9		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
10		5	5	3	5	3	10	10	10	3	5	1	1	3	3	67
11		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
12		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
13		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
14		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
15		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16		5	10	1	5	3	10	10	10	3	10	1	1	5	5	81
17		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
16 n3		5	10	3	5	3	10	10	10	3	10	1	1	5	5	79
17		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
18		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
19		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
20		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
24		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
25		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72
26		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
27		5	1	1	5	3	10	10	5	3	10	1	1	5	5	65
1		5	1	1	5	3	10	10	5	3	5	1	1	3	3	56
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
3		5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
4		5	5	5	5	3	10	10	10	3	1	1	1	1	1	61
5		5	5	5	5	3	10	10	10	3	1	1	1	1	1	61
6		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
7		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
8		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
9		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
10		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
11		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
12		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
13		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
14		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
15		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
16		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue	
60	17	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	16 w3	5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
	17	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	18	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	19	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	20	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	21	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	22	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	23	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	24	5	5	5	5	3	10	10	10	3	10	1	1	5	5	78	
	25	5	1	5	5	3	10	10	10	3	10	1	1	5	5	74	
	26	5	1	3	5	3	10	10	5	3	10	1	1	5	5	67	
	27	5	1	1	5	3	10	10	5	3	10	1	1	5	5	65	
	1 w4	5	1	1	5	3	10	10	5	3	1	1	1	1	1	1	48
	2	5	1	3	5	3	10	10	5	3	1	1	1	1	1	1	50
	3	5	5	5	5	3	10	10	10	3	1	1	1	1	1	1	61
	4	5	5	5	5	3	10	10	10	3	1	1	1	1	1	1	61
	5	5	5	3	5	3	10	10	10	3	1	1	1	1	1	1	59
	6	5	10	3	5	3	10	10	10	3	1	1	1	1	1	1	64
	7	5	10	1	5	3	10	10	10	3	1	1	1	1	1	1	62
	8	5	10	1	5	3	10	10	10	3	1	1	1	1	1	1	62
	9	5	10	3	5	3	10	10	10	3	5	1	1	1	3	3	72
	10	5	10	3	5	3	10	10	10	3	5	5	1	1	3	3	72
	11	5	10	3	5	3	10	10	10	3	1	1	1	1	1	1	64
	12	5	10	3	5	3	10	10	10	3	5	5	1	1	3	3	72
	13	5	10	1	5	3	10	10	10	3	3	10	1	1	5	5	79
	14	5	10	3	5	3	10	10	10	3	3	10	1	1	5	5	81
15	5	10	3	5	3	10	10	10	3	3	10	1	1	5	5	81	
16	5	10	3	5	3	10	10	10	3	3	10	1	1	5	5	81	
17	5	10	3	5	3	10	10	10	3	3	10	1	1	5	5	81	
61	16 w3	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	17	5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
	18	5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
	19	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	20	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	21	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	2	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	3	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	4	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	5	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum	
22		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
23		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
24		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76	
25		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78	
26		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67	
27		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67	
1 u4		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50	
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50	
3		5	5	5	5	3	10	10	10	3	1	1	1	1	1	61	
4		5	5	5	5	3	10	10	10	3	1	1	1	1	1	61	
5		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64	
6		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62	
7		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62	
8		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72	
9		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72	
10		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72	
11		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64	
12		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72	
13		5	10	3	5	3	10	10	10	3	10	1	1	5	5	79	
14		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
15		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72	
16		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
16 w3		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
17		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
18		5	10	3	5	3	10	10	10	3	10	1	1	5	5	79	
19		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
20		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
21		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79	
22		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
23		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
24		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76	
25		5	5	3	5	3	10	10	10	3	10	1	1	5	5	76	
26		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72	
27		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67	
1 u4		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50	

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
2		5	.	3	5	3	10	10	5	3	1	1	1	1	1	50
3		5	1	5	5	3	10	10	10	3	1	1	1	1	1	57
4		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
5		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
6		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
7		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
8		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
9		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
10		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
11		5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
12		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
13		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
14		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
15		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
16 W3		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
17		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
18		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
19		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
20		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
21		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
22		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
23		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
24		5	5	1	5	3	10	10	10	3	10	1	1	5	5	74
25		5	5	1	5	3	10	10	10	3	10	1	1	5	5	74
26		5	1	1	5	3	10	10	10	3	10	1	1	5	5	70
27		5	1	3	5	3	10	10	5	3	10	1	1	5	5	67
1 W4		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
3		5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
4		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
5		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
6		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
7		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
8		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
64	9	5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
	10	5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
	11	5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
	12	5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
	13	5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
	14	5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
	15	5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
	16	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
	17	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
	16 W3	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
	17	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
	18	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
	19	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
	20	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
	21	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
22	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
23	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
24	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
25	5	5	1	5	3	10	10	10	3	3	10	1	1	5	74	
26	5	5	1	5	3	10	10	10	3	3	10	1	1	5	70	
27	5	5	1	5	3	10	10	10	3	3	10	1	1	5	70	
1 W4	5	5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
2	5	5	1	1	5	3	10	10	5	3	1	1	1	1	1	48
3	5	5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
4	5	5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
5	5	5	5	3	5	3	10	10	10	3	1	1	1	1	1	57
6	5	5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
7	5	5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
8	5	5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
9	5	5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
10	5	5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
11	5	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
12	5	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
13	5	5	10	3	5	3	10	10	10	3	10	1	1	5	5	72
14	5	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
15	5	5	10	1	5	3	10	10	10	3	10	1	1	5	5	79

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking															
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sue	
65	16	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	17	5	10	3	5	3	10	10	10	3	10	1	1	5	5	81	
	16 w3	5	10	5	5	3	10	10	10	5	10	1	1	5	5	85	
	17	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	18	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	19	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	20	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	21	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	22	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	23	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	24	5	5	3	5	3	10	10	10	3	10	1	1	5	5	83	
	25	5	5	3	5	3	10	10	10	3	10	1	1	5	5	76	
	26	5	1	3	5	3	10	10	10	3	10	1	1	5	5	76	
	27	5	1	3	5	3	10	10	10	3	10	1	1	5	5	72	
	1 w4	5	1	3	5	3	10	10	10	5	3	1	1	1	1	1	50
	2	5	1	1	5	3	10	10	10	5	3	1	1	1	1	1	48
	3	5	1	1	5	3	10	10	10	5	3	1	1	1	1	1	48
	4	5	5	3	5	3	10	10	10	10	3	1	1	1	1	1	57
	5	5	5	3	5	3	10	10	10	10	3	1	1	1	1	1	59
	6	5	10	3	5	3	10	10	10	10	3	1	1	1	1	1	64
	7	5	10	3	5	3	10	10	10	10	3	1	1	1	1	1	64
	8	5	10	3	5	3	10	10	10	10	3	1	1	1	1	1	64
	9	5	10	3	5	3	10	10	10	10	3	1	1	1	1	1	64
	10	5	10	3	5	3	10	10	10	10	3	5	1	1	3	3	72
	11	5	10	1	5	3	10	10	10	10	3	10	1	1	5	5	79
	12	5	10	1	5	3	10	10	10	10	3	10	1	1	5	5	79
	13	5	10	3	5	3	10	10	10	10	3	10	1	1	5	5	81
14	5	10	3	5	3	10	10	10	10	3	10	1	1	5	5	81	
15	5	10	1	5	3	10	10	10	10	3	10	1	1	5	5	79	
16	5	10	1	5	3	10	10	10	10	3	10	1	1	5	5	79	
17	5	10	3	5	3	10	10	10	10	3	10	1	1	5	5	81	
66	16 w3	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	17	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	18	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	19	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
	20	5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	
		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83	

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
24		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
25		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
26		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
27		5	1	3	5	3	10	10	10	3	10	1	1	5	5	72
1 W4		5	1	3	5	3	10	10	5	3	5	1	1	3	3	58
2		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
3		5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
4		5	1	1	5	3	10	10	10	3	1	1	1	1	1	53
5		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
6		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
7		5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
8		5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
9		5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
10		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
11		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
12		5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
13		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
14		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
15		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
17		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
16 W3		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
18		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
19		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
20		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
24		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
25		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
26		5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
27		5	1	5	5	3	10	10	10	3	10	1	1	5	5	74

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Township	Range	Meridian	Ranking														Sue
			A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	
1	W4		5	1	3	5	3	10	10	5	3	10	1	1	3	5	69
2			5	1	5	5	3	10	10	5	3	5	1	1	3	3	60
3			5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
4			5	1	3	5	3	10	10	10	3	1	1	1	1	1	55
5			5	5	1	5	3	10	10	10	3	1	1	1	1	1	57
6			5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
7			5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
8			5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
9			5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
10			5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
11			5	10	1	5	3	10	10	10	3	5	1	1	3	3	70
12			5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
13			5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
14			5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
15			5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
16			5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
17			5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
16	W3		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
17			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
18			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
19			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
20			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
24			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
25			5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
26			5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
27			5	5	5	5	3	10	10	10	3	10	1	1	5	5	78
1	W4		5	1	5	5	3	10	10	5	3	5	1	1	3	3	60
2			5	1	5	5	3	10	10	5	3	1	1	1	1	1	52
3			5	1	3	5	3	10	10	5	3	1	1	1	1	1	50
4			5	1	3	5	3	10	10	5	3	1	1	1	1	1	55
5			5	5	1	5	3	10	10	10	3	1	1	1	1	1	57
6			5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
7			5	10	3	5	3	10	10	10	3	1	1	1	1	1	64

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														Sue
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	
8		5	10	5	5	3	10	10	10	3	1	1	1	1	1	66
9		5	10	9	5	3	10	10	10	3	1	1	1	1	1	70
10		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
11		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
12		5	10	1	5	3	10	10	10	3	10	1	1	5	5	79
13		5	10	3	5	3	10	10	5	3	10	1	1	5	5	76
14		5	10	3	5	3	10	10	5	3	10	1	1	5	5	76
15		5	10	1	5	3	10	10	5	3	10	1	1	5	5	74
16		5	10	1	5	3	10	10	5	3	10	1	1	5	5	74
17		5	10	3	5	3	10	10	5	3	10	1	1	5	5	76
16 u3		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
17		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
18		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
19		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
20		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
21		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
22		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
23		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
24		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
25		5	10	5	5	3	10	10	10	3	10	1	1	5	5	83
26		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
27		5	10	3	5	3	10	10	10	3	10	1	1	5	5	81
1 u4		5	1	5	5	3	10	10	10	3	1	1	1	1	1	57
2		5	1	5	5	3	10	10	5	3	1	1	1	1	1	52
3		5	1	5	5	3	10	10	5	3	1	1	1	1	1	52
4		5	1	5	5	3	10	10	10	3	1	1	1	1	1	55
5		5	5	3	5	3	10	10	10	3	1	1	1	1	1	59
6		5	5	1	5	3	10	10	10	3	1	1	1	1	1	57
7		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
8		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
9		5	10	5	5	3	10	10	10	3	5	1	1	3	3	74
10		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
11		5	10	3	5	3	10	10	10	3	5	1	1	3	3	72
12		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62
13		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
14		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64

Table B-3. Hydrostratigraphic Unit Evaluation - Mannville Group Ranking

Area		Ranking														
Township	Range Meridian	A1	A2	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	C1	C2	Sum
15		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
16		5	10	3	5	3	10	10	10	3	1	1	1	1	1	64
17		5	10	1	5	3	10	10	10	3	1	1	1	1	1	62

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBMA	Mannville
55	16	w3	87	65	83
	17		85	65	83
	18		85	65	83
	19		85	65	83
	20		85	65	81
	21		83	65	76
	22		78	64	74
	23		86	60	70
	24		85	60	67
	25		89	60	67
	26		91	60	69
	27		96	60	69
	1	w4	98	60	69
	2		103	64	67
	3		103	69	65
	4		103	92	65
	5		103	92	67
	6		103	94	67
	7		103	94	67
	8		103	94	67
	9		103	94	69
	10		103	94	67
	11		103	94	67
	12		103	94	70
	13		103	94	70
	14		103	94	74
	15		103	99	76
	16		103	99	76
	17		103	99	83
56	16	w3	85	65	83
	17		85	65	83
	18		83	65	83
	19		83	65	83
	20		83	65	83
	21		78	69	81
	22		73	64	76
	23		73	64	74
	24		69	60	70
	25		91	60	67
	26		91	60	67
	27		98	60	69
	1	w4	103	62	58
	2		103	62	50
	3		103	57	48
	4		103	92	48
	5		103	92	48
	6		103	94	56
	7		103	94	58
	8		103	94	58
	9		103	94	60

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBNA	Mannville
57	10	W3	103	94	72
	11		103	94	72
	12		103	94	74
	13		103	94	76
	14		103	94	74
	15		103	99	79
	16		103	99	79
	17		103	99	81
	16		78	65	81
	17		78	65	83
	18		78	65	83
	19		78	65	83
	20		83	65	83
	21		83	69	83
	22		78	64	76
	23		78	64	76
	24		69	60	72
	25		85	60	65
	26		91	60	67
	27		96	60	67
	1	W4	98	60	58
	2		103	53	50
	3		103	57	48
	4		103	62	48
	5		103	90	48
	6		103	92	50
	7		103	92	55
	8		103	92	63
	9		103	94	78
	10		103	94	67
	11		103	94	65
	12		103	94	65
	13		103	94	81
	14		103	94	81
	15		103	99	81
	16		103	99	81
	17		103	99	81
58	16		78	65	81
	17		78	65	83
	18		78	65	83
	19		78	65	83
	20		78	65	83
	21		78	65	83
	22		78	69	83
	23		73	64	76
	24		73	64	76
	25		85	60	67
	26		91	60	65
	27		91	60	65
	1	W4	98	53	58

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CDMA	Mannville
	2		103	53	48
	3		103	57	50
	4		103	62	50
	5		103	62	55
	6		103	67	59
	7		103	90	59
	8		103	92	67
	9		103	94	76
	10		103	94	67
	11		103	94	62
	12		103	94	72
	13		103	94	81
	14		103	94	81
	15		103	99	81
	16		103	99	79
	17		103	99	79
59	16	w3	78	65	81
	17		78	65	81
	18		78	65	81
	19		78	65	83
	20		78	65	83
	21		78	65	83
	22		78	65	83
	23		73	60	78
	24		73	60	78
	25		69	60	72
	26		91	60	67
	27		91	60	65
	1	w4	98	53	56
	2		103	53	50
	3		103	57	55
	4		103	62	61
	5		103	62	61
	6		103	66	59
	7		103	90	59
	8		103	92	64
	9		103	92	70
	10		103	94	79
	11		103	94	70
	12		103	94	70
	13		103	94	79
	14		103	94	79
	15		103	99	79
	16		103	99	79
	17		103	99	81
60	16	w3	78	65	79
	17		78	65	81
	18		78	65	81
	19		78	65	81
	20		78	65	81

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CDWA	Mannville
	21		78	65	83
	22		78	65	83
	23		78	65	83
	24		73	64	78
	25		69	60	74
	26		85	60	67
	27		91	60	65
	1	W4	91	60	48
	2		98	60	50
	3		103	64	61
	4		103	64	61
	5		103	67	59
	6		103	67	64
	7		103	90	62
	8		103	92	62
	9		103	92	72
	10		103	94	72
	11		103	94	64
	12		103	94	72
	13		103	94	79
	14		103	94	81
	15		103	99	81
	16		103	99	81
	17		103	99	81
61	16	W3	78	65	81
	17		78	65	79
	18		78	65	79
	19		78	65	81
	20		78	65	81
	21		78	65	81
	22		78	65	81
	23		78	65	81
	24		73	60	76
	25		73	60	78
	26		85	56	67
	27		91	56	67
	1	W4	91	53	50
	2		98	53	50
	3		103	57	61
	4		103	57	61
	5		103	62	64
	6		103	62	62
	7		103	90	62
	8		103	92	72
	9		103	92	72
	10		103	94	72
	11		103	94	64
	12		103	94	72
	13		103	94	79
	14		103	94	81

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBWA	Mannville
62	15	w3	103	99	72
	16		103	94	83
	17		103	94	83
	16		78	65	81
	17		78	65	81
	18		78	65	81
	19		78	65	79
	20		78	65	79
	21		78	65	79
	22		78	65	81
	23		78	65	81
	24		73	60	76
	25		73	64	76
	26		69	60	72
	27		91	60	67
	1	w4	91	53	50
	2		98	53	50
	3		103	53	57
	4		103	57	59
	5		103	62	64
	6		103	62	62
	7		103	62	64
	8		103	90	72
	9		103	92	72
	10		103	94	72
	11		103	94	66
	12		103	94	64
	13		103	94	81
	14		103	94	79
63	15	w3	103	94	81
	16		103	94	81
	17		103	94	83
	16		73	65	83
	17		78	65	81
	18		78	65	81
	19		78	65	81
	20		78	65	81
	21		78	65	81
	22		78	65	79
	23		78	65	79
	24		73	60	74
	25		73	60	74
	26		69	60	70
	27		85	60	67
	1	w4	91	53	50
	2		91	53	50
	3		103	53	55
	4		103	57	59
	5		103	62	62
	6		103	62	62

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBNA	Nannville
	7		103	62	70
	8		103	90	70
	9		103	90	70
	10		103	92	72
	11		103	92	72
	12		103	94	72
	13		103	94	72
	14		103	94	79
	15		103	94	81
	16		103	94	81
	17		103	94	83
64	16	w3	73	65	83
	17		73	65	83
	18		73	65	83
	19		73	65	83
	20		73	65	81
	21		73	65	81
	22		73	65	81
	23		78	65	81
	24		73	65	81
	25		73	60	74
	26		69	56	70
	27		85	60	70
	1	w4	91	53	48
	2		91	53	48
	3		103	53	55
	4		103	57	59
	5		103	57	57
	6		103	62	62
	7		103	62	64
	8		103	62	64
	9		103	62	62
	10		103	90	62
	11		103	92	81
	12		103	94	81
	13		103	94	72
	14		103	94	81
	15		103	94	79
	16		103	94	81
	17		103	94	81
65	16	w3	69	65	85
	17		69	65	83
	18		69	65	63
	19		69	65	83
	20		73	65	83
	21		73	65	83
	22		73	65	83
	23		73	65	83
	24		73	65	76
	25		73	60	76

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBMA	Mannville
	26		73	56	72
	27		69	56	72
	1	n4	89	49	50
	2		91	53	48
	3		91	53	48
	4		103	57	57
	5		103	57	59
	6		103	62	64
	7		103	62	64
	8		103	62	64
	9		103	62	64
	10		103	90	72
	11		103	92	79
	12		103	92	79
	13		103	94	81
	14		103	94	81
	15		103	94	79
	16		103	94	79
	17		103	94	81
66	16	n3	-	65	83
	17		-	65	83
	18		-	65	83
	19		-	65	83
	20		-	65	83
	21		-	65	83
	22		65	65	83
	23		65	65	83
	24		69	65	83
	25		69	60	78
	26		69	60	78
	27		69	56	72
	1	n4	85	53	58
	2		91	53	50
	3		91	53	50
	4		96	53	53
	5		96	57	59
	6		96	62	64
	7		103	62	66
	8		103	62	66
	9		103	62	66
	10		103	69	72
	11		103	90	70
	12		103	92	70
	13		103	94	79
	14		103	94	81
	15		103	94	81
	16		103	94	79
	17		103	90	79
67	16	n3	-	65	83
	17		-	65	83

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CBWA	Mannville
	18		-	65	83
	19		-	65	83
	20		-	65	83
	21		-	65	83
	22		-	65	83
	23		-	65	83
	24		-	65	83
	25		-	60	78
	26		-	60	78
	27		-	56	74
	1	W4	-	56	69
	2		77	49	60
	3		77	53	50
	4		86	53	55
	5		96	57	57
	6		96	62	64
	7		96	62	66
	8		96	62	66
	9		96	62	66
	10		96	69	81
	11		96	90	70
	12		96	92	79
	13		96	94	79
	14		96	94	79
	15		96	94	79
	16		96	94	79
	17		96	94	81
68	16	W3	-	65	83
	17		-	65	83
	18		-	65	83
	19		-	65	83
	20		-	65	83
	21		-	65	83
	22		-	65	83
	23		-	65	83
	24		-	65	83
	25		-	65	83
	26		-	60	78
	27		-	56	78
	1	W4	-	49	60
	2		-	49	52
	3		-	53	50
	4		-	53	55
	5		-	57	57
	6		82	57	64
	7		86	62	64
	8		96	62	66
	9		96	74	70
	10		82	81	81
	11		82	90	81

Table B-4. Hydrostratigraphic Unit Evaluation - Summary of Scores

Area			Formation		
Township	Range	Meridian	Cambrian	CDMA	Mannville
	12		82	92	79
	13		82	94	76
	14		82	94	76
	15		82	94	74
	16		82	94	74
	17		82	94	76
69	16	w3	-	65	83
	17		-	65	83
	18		-	65	83
	19		-	65	83
	20		-	65	83
	21		-	65	83
	22		-	65	83
	23		-	65	83
	24		-	65	83
	25		-	65	83
	26		-	60	81
	27		-	60	81
	1	w4	-	49	57
	2		-	49	52
	3		-	49	52
	4		-	53	55
	5		-	57	59
	6		-	57	57
	7		-	62	64
	8		-	62	64
	9		-	62	74
	10		-	85	72
	11		-	87	72
	12		-	92	62
	13		-	94	64
	14		-	94	64
	15		-	94	64
	16		-	94	64
	17		-	67	62

APPENDIX C

Study Area Evaluation - Rankings

Table C-1. Siting of Background Monitoring Facilities - Summary of Ranking

Township	Area		Ranking						Sum
	Range	Meridian	A1	B1	B2	B3	C1	C2	
55	26	W3	1	1	3	3	5	1	14
	27		1	1	3	3	3	1	12
	1	W4	1	1	3	3	3	5	16
	2		1	1	3	3	5	5	18
	3		1	1	5	5	5	5	22
	4		3	1	5	5	3	5	22
	5		3	3	5	5	1	5	22
	6		3	3	5	5	1	5	22
	7		3	3	5	5	3	5	24
56	8		3	3	5	5	5	5	26
	26	W3	1	1	3	3	5	1	14
	27		1	1	3	3	5	1	14
	1	W4	1	1	3	3	1	5	14
	2		3	1	3	3	5	5	20
	3		1	1	3	3	5	5	18
	4		1	1	5	5	3	5	20
	5		3	1	5	5	1	5	20
	6		1	1	5	5	1	5	18
57	7		1	1	5	5	3	5	20
	8		1	3	5	5	5	5	24
	9		1	5	5	5	5	5	26
	26	W3	1	1	3	3	5	1	14
	27		1	1	3	3	5	1	14
	1	W4	1	1	3	3	5	5	18
	2		1	1	3	3	5	5	18
	3		3	1	3	3	5	5	20
	4		1	1	3	3	5	5	18
58	5		1	1	5	5	3	5	20
	6		1	1	5	5	3	5	20
	7		1	3	5	5	3	5	22
	8		1	3	5	5	5	5	24
	10		3	3	5	5	5	5	26
	11		3	1	5	5	5	5	24
	12		3	1	5	5	5	5	24
	27	W3	1	1	3	3	5	1	14
	1	W4	1	1	3	3	5	5	18
59	2		1	1	3	3	5	5	18
	3		1	1	3	3	5	5	18
	4		1	1	3	3	1	5	14
	5		1	1	3	3	1	5	14
	6		1	1	5	5	5	5	22
	7		3	3	5	5	5	5	26
	8		3	3	5	5	5	5	26
	10		3	3	5	5	5	5	26
	11		5	1	5	5	1	5	22
59	12		5	3	5	5	3	5	26
	27	W3	1	1	3	3	5	1	14
	1	W4	1	1	3	3	3	5	16
	2		1	1	3	3	1	5	14
	3		1	1	3	3	3	5	16

Table C-1. Siting of Background Monitoring Facilities - Summary of Ranking

Area		Ranking						Sum
Township	Range Meridian	A1	B1	B2	B3	C1	C2	
60	4	1	1	3	3	1	5	14
	5	3	1	3	3	3	5	18
	6	1	1	3	3	5	5	18
	7	1	1	5	5	5	5	22
	8	1	3	5	5	5	5	24
	9	1	1	5	5	5	5	22
	11	5	1	5	5	3	5	24
	12	5	1	5	5	5	5	26
	27 W3	1	1	3	3	5	1	14
	1 W4	1	1	3	3	5	5	18
	2	1	1	3	3	3	5	16
	3	3	1	3	3	5	5	20
	4	3	1	3	3	3	5	18
	5	3	1	3	3	5	5	20
	6	3	1	3	3	5	5	20
	7	1	1	5	5	5	5	22
	8	3	1	5	5	5	5	24
	9	3	3	5	5	5	5	26
	10	5	3	5	5	5	5	28
	11	5	3	5	5	5	5	28
61	12	5	3	5	5	5	5	28
	27 W3	1	1	3	3	5	1	14
	1 W4	1	1	3	3	3	5	16
	2	1	1	3	3	1	5	14
	3	3	1	3	3	3	5	18
	4	3	1	3	3	5	5	20
	5	3	1	3	3	5	5	20
	6	3	1	3	3	5	5	20
	7	1	1	5	5	5	5	22
	8	3	3	5	5	5	5	26
	9	3	3	5	5	5	5	26
	10	5	3	5	5	5	5	28
	11	5	3	5	5	5	5	28
	12	5	3	5	5	5	5	28
	15	5	3	5	5	5	5	28
	27 W3	1	1	3	3	5	1	14
	1 W4	1	1	3	3	3	5	16
	2	1	1	3	3	3	5	16
	3	3	1	3	3	5	5	20
	4	3	1	3	3	3	5	18
62	5	3	1	3	3	5	5	20
	6	3	1	3	3	5	5	20
	7	1	1	3	3	3	5	16
	8	1	1	5	5	1	5	18
	9	3	3	5	5	3	5	24
	10	5	5	5	5	5	5	30
	11	5	5	5	5	5	5	30
	12	5	5	5	5	5	5	30
	27 W3	1	1	3	3	5	1	14
	1 W4	1	1	3	3	5	5	18
63	2	1	1	3	3	3	5	16
	3	3	1	3	3	5	5	20
	4	3	1	3	3	3	5	18
	5	3	1	3	3	5	5	20
	6	3	1	3	3	5	5	20
	7	1	1	3	3	3	5	16
	8	1	1	5	5	1	5	18
	9	3	3	5	5	3	5	24
	10	5	5	5	5	5	5	30
	11	5	5	5	5	5	5	30
	12	5	5	5	5	5	5	30
	27 W3	1	1	3	3	5	1	14
	1 W4	1	1	3	3	5	5	18

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Area			Ranking						
Township	Range	Meridian	A1	B1	B2	B3	C1	C2	Sum
64	2		1	1	3	3	5	5	18
	3		1	1	3	3	3	5	16
	4		3	1	3	3	3	5	18
	5		5	1	3	3	3	5	20
	6		3	1	3	3	3	5	18
	7		1	1	3	3	3	5	16
	8		1	1	5	5	1	5	18
	9		1	1	5	5	3	5	20
	10		3	3	5	5	5	5	26
	11		3	3	5	5	5	5	26
	12		5	3	5	5	5	5	28
	13		5	3	5	5	1	5	24
	27	W3	1	1	3	3	5	1	14
	1	W4	1	1	3	3	5	5	18
	2		1	1	3	3	3	5	16
	3		1	1	3	3	1	5	14
65	4		3	1	3	3	1	5	16
	5		3	1	3	3	3	5	18
	6		3	1	3	3	1	5	16
	7		3	1	3	3	3	5	18
	8		1	1	3	3	3	5	16
	9		1	1	3	3	5	5	18
	10		1	1	5	5	5	5	22
	13		5	3	5	5	1	5	24
	27	W3	1	1	3	3	5	1	14
	1	W4	1	1	3	3	3	5	16
	2		1	1	3	3	1	5	14
	3		1	1	3	3	1	5	14
	4		3	1	3	3	3	5	18
	5		3	1	3	3	3	5	18
	6		5	1	3	3	3	5	20
	66	7		3	1	3	3	5	5
8			3	1	3	3	5	1	18
9			3	1	3	3	5	5	20
10			1	1	5	5	5	5	22
27		W3	1	1	3	3	5	1	14
1		W4	1	1	3	3	5	5	18
2			1	1	3	3	3	5	16
3			1	1	3	3	3	5	16
4			1	1	3	3	3	5	16
5			3	1	3	3	1	5	16
6			3	1	3	3	3	5	18
7			5	1	3	3	5	5	22
8			3	1	3	3	5	5	20
9			3	1	3	3	5	5	20
10			1	1	3	3	5	5	18
11			1	1	5	5	5	5	22
67	12		3	3	5	5	5	5	26
	1	W4	1	1	3	3	5	1	14
	2		1	1	3	3	5	1	14

Table C-1. Siting of Background Monitoring Facilities - Summary of Ranking

Area			Ranking						
Township	Range	Meridian	A1	B1	B2	B3	C1	C2	Sum
68		3	1	1	3	3	5	5	18
		4	1	1	3	3	1	5	14
		5	3	1	3	3	3	5	18
		6	3	1	3	3	3	5	18
		7	3	1	3	3	5	1	16
		8	3	1	3	3	5	1	16
		9	3	1	3	3	5	1	16
		11	5	1	5	5	5	5	26
		1 W4	1	1	1	1	5	5	14
		2	1	1	3	3	5	5	18
		3	1	1	3	3	5	5	18
		4	1	1	3	3	5	5	18
		5	1	1	3	3	5	5	18
		6	1	1	3	3	5	5	18
		7	1	1	3	3	5	5	18
		8	1	1	3	3	5	1	14
69		9	3	1	3	3	5	1	16
		1 W4	1	1	1	1	5	1	10
		2	1	1	3	3	5	1	14
		3	1	1	3	3	5	5	18
		4	1	1	3	3	5	1	14
		5	1	1	3	3	5	1	14
		6	1	1	3	3	5	1	14
		7	1	1	3	3	5	1	14
		8	1	1	3	3	5	1	14
		9	1	1	3	3	5	1	14
		10	1	1	3	3	5	1	14
		11	1	1	3	3	5	1	14
	12	1	1	5	5	5	1	18	

Table C-2. Siting of Impact Monitoring Facilities - Summary of Ranking

Area		Ranking								Sum
Township	Range Meridian	A1	B1	B2	B3	C1	C2	C3	C4	
55	26 W3	5	5	3	3	3	1	1	1	22
	27	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
	2	5	5	3	3	3	5	1	1	26
	3	5	5	1	1	3	5	1	1	22
	4	5	5	1	1	3	5	1	1	22
	5	5	3	1	1	5	5	3	3	26
	6	5	3	1	1	5	5	5	3	28
56	7	5	3	1	1	3	5	1	1	20
	8	5	3	1	1	3	5	1	1	20
	26 W3	5	5	3	3	3	1	1	1	22
	27	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	5	5	3	1	30
	2	5	5	3	3	3	5	1	1	26
	3	5	5	3	3	3	5	1	1	26
	4	5	5	1	1	3	5	1	1	22
57	5	5	5	1	1	5	5	3	1	26
	6	5	5	1	1	5	5	5	1	28
	7	5	5	1	1	3	5	1	3	24
	8	5	3	1	1	3	5	1	3	22
	9	5	1	1	1	1	5	1	1	16
	26 W3	5	5	3	3	3	1	1	1	22
	27	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
58	2 W4	5	5	3	3	3	5	1	1	26
	3	5	5	3	3	3	5	1	1	26
	4	5	5	3	3	3	5	1	1	26
	5	5	5	1	1	3	5	1	1	22
	6	5	5	1	1	3	5	1	1	22
	7	5	3	1	1	3	5	1	1	20
	8	5	3	1	1	3	5	1	1	20
	10	3	3	1	1	3	5	1	1	18
59	11	3	5	1	1	3	5	1	1	20
	12	3	5	1	1	3	5	1	1	20
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
	2	5	5	3	3	3	5	1	1	26
	3	5	5	3	3	3	5	1	1	26
	4	5	5	3	3	5	5	3	1	30
	5	5	5	3	3	5	5	5	3	34
59	6	5	5	1	1	3	5	1	1	22
	7	3	3	1	1	3	5	1	1	18
	8	3	3	1	1	1	5	1	1	16
	10	3	3	1	1	3	5	1	1	18
	11	1	5	1	1	5	5	3	1	22
	12	1	3	1	1	3	5	1	1	16
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
59	2	5	5	3	3	5	5	3	1	30
	3	5	5	3	3	3	5	1	1	26

Table C-2. Siting of Impact Monitoring Facilities - Summary of Ranking

Area		Ranking								Sum
Township	Range Meridian	A1	B1	B2	B3	C1	C2	C3	C4	
60	4	3	5	3	3	5	5	3	1	28
	5	3	5	3	3	3	5	1	1	24
	6	3	5	3	3	3	5	1	1	24
	7	3	5	1	1	1	5	1	1	18
	8	1	3	1	1	1	5	1	1	14
	9	1	5	1	1	1	5	1	1	16
	11	1	5	1	1	3	5	1	1	18
	12	1	5	1	1	3	5	1	1	18
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
	2	5	5	3	3	3	5	1	1	26
	3	5	5	3	3	3	5	1	1	26
	4	3	5	3	3	3	5	1	1	24
	5	3	5	3	3	3	5	1	1	24
	6	1	5	3	3	3	5	1	1	22
	7	1	5	1	1	1	5	1	1	16
	8	1	5	1	1	1	5	1	1	16
	9	1	3	1	1	1	5	1	1	14
	10	1	3	1	1	1	5	1	1	14
	11	1	3	1	1	3	5	1	1	16
61	12	1	3	1	1	1	5	1	1	14
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
	2	5	5	3	3	3	5	3	1	28
	3	3	5	3	3	3	5	3	1	24
	4	3	5	3	3	5	5	3	1	28
	5	1	5	3	3	3	5	3	5	28
	6	1	5	3	3	3	5	3	1	24
	7	1	5	1	1	3	5	3	1	20
	8	1	3	1	1	3	5	3	1	18
	9	1	3	1	1	3	5	3	1	18
	10	1	3	1	1	1	5	3	1	16
	11	1	3	1	1	1	5	3	1	16
	12	1	3	1	1	1	5	3	1	16
	15	1	3	1	1	3	5	3	1	18
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
	2	5	5	3	3	3	5	3	1	28
	3	3	5	3	3	3	5	1	1	24
	4	3	5	3	3	3	5	1	1	24
62	5	1	5	3	3	3	5	1	1	22
	6	1	5	3	3	3	5	1	1	22
	7	1	5	3	3	3	5	1	1	22
	8	1	5	1	1	5	5	1	1	20
	9	1	3	1	1	3	5	1	1	16
	10	1	3	1	1	3	5	1	1	16
	11	1	1	1	1	1	5	1	1	12
	12	1	3	1	1	3	5	1	1	16
	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26
63	27 W3	5	5	3	3	3	1	1	1	22
	1 W4	5	5	3	3	3	5	1	1	26

Table C-2. Siting of Impact Monitoring Facilities - Summary of Ranking

Area			Ranking									
Township	Range	Meridian	A1	B1	B2	B3	C1	C2	C3	C4	Sum	
	2		5	5	3	3	3	5	1	1	26	
	3		5	5	3	3	3	5	1	1	26	
	4		3	5	3	3	3	5	1	1	24	
	5		1	5	3	3	3	5	1	1	22	
	6		1	5	3	3	3	5	1	1	22	
	7		1	5	3	3	3	5	1	1	22	
	8		1	5	1	1	5	5	5	1	24	
	9		1	5	1	1	3	5	1	1	18	
	10		1	3	1	1	3	5	1	1	16	
	11		1	3	1	1	3	5	1	1	16	
	12		1	3	1	1	3	5	1	1	16	
	13		1	3	1	1	5	5	3	1	20	
	64	27 W3		5	5	3	3	3	1	1	1	22
1 W4			5	5	3	3	3	5	1	1	26	
2			5	5	3	3	3	5	1	1	26	
3			5	5	3	3	5	5	3	5	34	
4			3	5	3	3	5	5	3	1	28	
5			3	5	3	3	3	5	1	1	24	
6			1	5	3	3	5	5	5	1	28	
7			1	5	3	3	3	5	1	1	22	
8			1	5	3	3	3	5	1	1	22	
9			1	5	3	3	3	5	1	1	22	
10			1	5	1	1	3	5	1	1	18	
13			1	3	1	1	5	5	3	1	20	
65		27 W3		5	5	3	3	3	1	1	1	22
	1 W4		5	5	3	3	3	5	1	1	26	
	2		5	5	3	3	5	5	3	3	32	
	3		5	5	3	3	5	5	5	3	34	
	4		3	5	3	3	3	5	1	1	24	
	5		3	5	3	3	3	5	1	5	28	
	6		1	5	3	3	3	5	1	1	22	
	7		1	5	3	3	3	5	1	1	22	
	8		1	5	3	3	3	1	1	1	18	
	9		1	5	3	3	1	5	1	1	20	
	10		1	5	1	1	1	5	1	1	16	
	66	27 W3		5	5	3	3	3	1	1	1	22
		1 W4		5	5	3	3	3	5	1	1	26
2			5	5	3	3	3	5	1	1	26	
3			5	5	3	3	3	5	3	1	28	
4			3	5	3	3	3	5	1	1	24	
5			3	5	3	3	5	5	5	1	30	
6			3	5	3	3	3	5	1	1	24	
7			1	5	3	3	3	5	1	1	22	
8			1	5	3	3	1	5	1	1	20	
9			1	5	3	3	1	5	1	1	20	
10			1	5	3	3	1	5	1	1	20	
11			1	5	1	1	3	5	1	1	18	
12			1	5	1	1	3	5	1	1	18	
67	1 W4		5	5	3	3	1	1	1	1	20	
	2 W4		5	5	3	3	3	1	1	1	22	

Table C-2. Siting of Impact Monitoring Facilities - Summary of Ranking

Area		Ranking								Sum
Township	Range Meridian	A1	B1	B2	B3	C1	C2	C3	C4	
68	3	5	5	3	3	3	5	1	1	26
	4	5	5	3	3	5	5	1	1	28
	5	3	5	3	3	3	5	1	1	24
	6	3	5	3	3	3	5	1	1	24
	7	3	5	3	3	3	1	1	1	20
	8	3	5	3	3	1	1	1	1	18
	9	3	5	3	3	1	1	1	1	18
	11	3	5	1	1	1	5	1	1	18
	1 W4	5	5	5	5	1	5	1	1	28
	2	5	5	3	3	1	5	1	1	24
	3	5	5	3	3	3	5	1	1	26
	4	5	5	3	3	3	5	1	1	26
	5	5	5	3	3	3	5	1	1	26
	6	5	5	3	3	1	5	1	1	24
	7	5	5	3	3	1	5	1	1	24
69	8	3	5	3	3	1	1	1	1	18
	9	3	5	3	3	1	1	1	1	18
	1 W4	5	5	5	5	1	1	1	1	24
	2	5	5	3	3	1	1	1	1	20
	3	5	5	3	3	1	5	1	1	24
	4	5	5	3	3	1	1	1	1	20
	5	5	5	3	3	1	1	1	1	20
	6	5	5	3	3	1	1	1	1	20
	7	5	5	3	3	1	1	1	1	20
	8	5	5	3	3	1	1	1	1	20
	9	5	5	3	3	1	1	1	1	20
	10	5	5	3	3	1	1	1	1	20
	11	5	5	3	3	1	1	1	1	20
	12	5	5	3	3	1	1	1	1	20

APPENDIX D

Companies Providing Price Quotations

Barringer-Magenta
304 Carlingview Drive
Rexdale, Ontario M9W 5G2

Baski Water Instruments
Toronto, Ontario

R.P. Bennett
P.O. Box 7644
Amarillo, Texas 79114

Bondar Clegg
764 Belfast Road
Ottawa, Ontario K1G 0Z5

Canus Plastics
300 Lisgar Street
Ottawa, Ontario

Core Laboratories
1540 - 25 Avenue N.E.
Calgary, Alberta

Fisher Scientific
112 Colonnade Road
Nepean, Ontario K2E 7L6

Geotech
4500 - 5th Street S.E.
Calgary, Alberta T2E 7C3

Hewlett-Packard Canada Ltd.
6877 Goreway Drive
Mississauga, Ontario L4V 1M8

Hoskin Scientific
1156 Speers Road
Oakville, Ontario L6A 2X4

In-Situ Inc.
209 Grand Avenue
Laramie, Wyoming 82070

Lynes United Services Ltd.
309 - 2 Avenue S.W.
Calgary, Alberta T2P 0C5

Milchem Canada Ltd.
309 - 2 Avenue S.W.
Calgary, Alberta T2P 0C5

Northeastern Drilling Ltd.
1015 - 4th Street S.W.
Calgary, Alberta T2P 1J4

Newsco Well Services
1300, 801 - 6th Avenue S.W.
Calgary, Alberta T2P 4E1

Petroleum Services Association Canada
414 - 603 7th Avenue S.W.
Calgary, Alberta

Schlumberger Canada
24th Floor Moneco Place
801 - 6th Avenue S.W.
Calgary, Alberta T2P 3W2

Sedco Drilling
Box 6680 Postal Station "D"
Calgary, Alberta T2P 2V8

SRP Control Systems
Toronto, Ontario

University of Waterloo
University Avenue
Waterloo, Ontario

Westburne
535 - 7th Avenue S.W.
Calgary, Alberta T2P 0Y4

Zagerman
1630 Star Top Road
Ottawa, Ontario

Zenon Environmental Inc.
845 Harrington Court
Burlington, Ontario L7A 3P3